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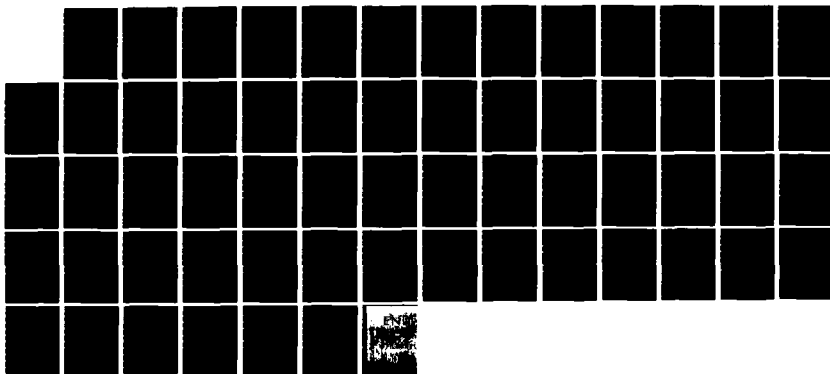
COMPUTER SIMULATION OF BUILDINGS COOLED BY NATURAL  
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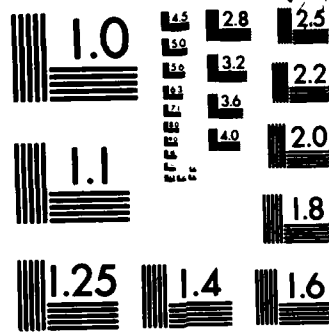
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AUTHOR: S. Ashley

DATE: May 1983

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# NOTE

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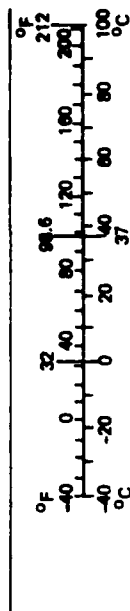
# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
in ft yd mi	inches	<b>LENGTH</b> *2.5 30 0.9 1.6	centimeters	cm
	feet		centimeters	cm
	yards		meters	m
	miles		kilometers	km
in <sup>2</sup> ft <sup>2</sup> yd <sup>2</sup> mi <sup>2</sup>	square inches	<b>AREA</b> 6.5 0.09 0.8 2.6 0.4	square centimeters	cm <sup>2</sup>
	square feet		square meters	m <sup>2</sup>
	square yards		square meters	m <sup>2</sup>
	square miles		square kilometers	km <sup>2</sup>
oz lb	ounces	<b>MASS (weight)</b> 28 0.45 0.9	grams	g
	pounds		kilograms	kg
	short tons		tonnes	t
	(2,000 lb)			
tsp Tbsp fl oz c pt qt gal ft <sup>3</sup> yd <sup>3</sup>	teaspoons	<b>VOLUME</b> 5 15 30 0.24 0.47 0.95 3.8 0.03 0.76	milliliters	ml
	tablespoons		milliliters	ml
	fluid ounces		milliliters	ml
	cups		liters	l
	pints		liters	l
	quarts		liters	l
	gallons		liters	l
	cubic feet		cubic meters	m <sup>3</sup>
	cubic yards		cubic meters	m <sup>3</sup>
°F	Fahrenheit temperature	<b>TEMPERATURE (exact)</b> 5/9 (after subtracting 32)	Celsius temperature	°C

## Approximate Conversions from Metric Measures

When You Know	Multiply by	To Find	Symbol
millimeters centimeters meters kilometers	<b>LENGTH</b> 0.04 0.4 3.3 1.1 0.6	inches	in
		inches	in
		feet	ft
		yards	yd
square centimeters square meters square kilometers hectares (10,000 m <sup>2</sup> )	<b>AREA</b> 0.16 1.2 0.4 2.5	square inches	in <sup>2</sup>
		square yards	yd <sup>2</sup>
		square miles	mi <sup>2</sup>
		acres	
grams kilograms tonnes (1,000 kg)	<b>MASS (weight)</b> 0.035 2.2 1.1	ounces	oz
		pounds	lb
		short tons	
milliliters liters liters cubic meters cubic meters	<b>VOLUME</b> 0.03 2.1 1.06 0.26 35 1.3	fluid ounces	fl oz
		pints	pt
		quarts	qt
		gallons	gal
		cubic feet	ft <sup>3</sup>
		cubic yards	yd <sup>3</sup>
°C	Celsius temperature	<b>TEMPERATURE (exact)</b> 9/5 (then add 32)	°F



\*1 in. = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10-286.

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mechanically induced air flow rates, type of building construction, interior heat loads, and the number of people in the building.

The application of this computer model includes the study of the natural ventilation performance of a building, the influence of natural infiltration on mechanical ventilation systems, and the study of smoke in the event of a fire.

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## Chapter 1

### INTRODUCTION

This report presents information covering the experimental and theoretical basis used to develop the computer simulation of natural ventilation cooling of buildings. Computer input and output and an application example are included.

The natural ventilation cooling of a building is dependent on (1) weather, (2) shape and orientation of building, and (3) shape and position of doors and windows (and whether open or closed). Other influences include the operation of mechanical ventilation systems and the transient effects caused by opening and closing doors.

Evaluation of rates of ventilation and interior effective temperatures for all but the very simplest of buildings is not practicable without the use of computing techniques.

The computer program predicts ventilation rates, mean interior air speed and direction of air flow, interior temperatures, and interior effective temperatures for a given set of conditions. These conditions are namely meteorological wind speed and direction, air temperature, air leakage characteristics of openings, the mechanically induced air flow rates, type of building construction, and the number of people in the building.

The application of this computer model (Figure 1.1) includes the study of the natural ventilation performance of buildings, the influence of natural infiltration on mechanical ventilation systems, and the study of the movement of smoke in the event of a fire.

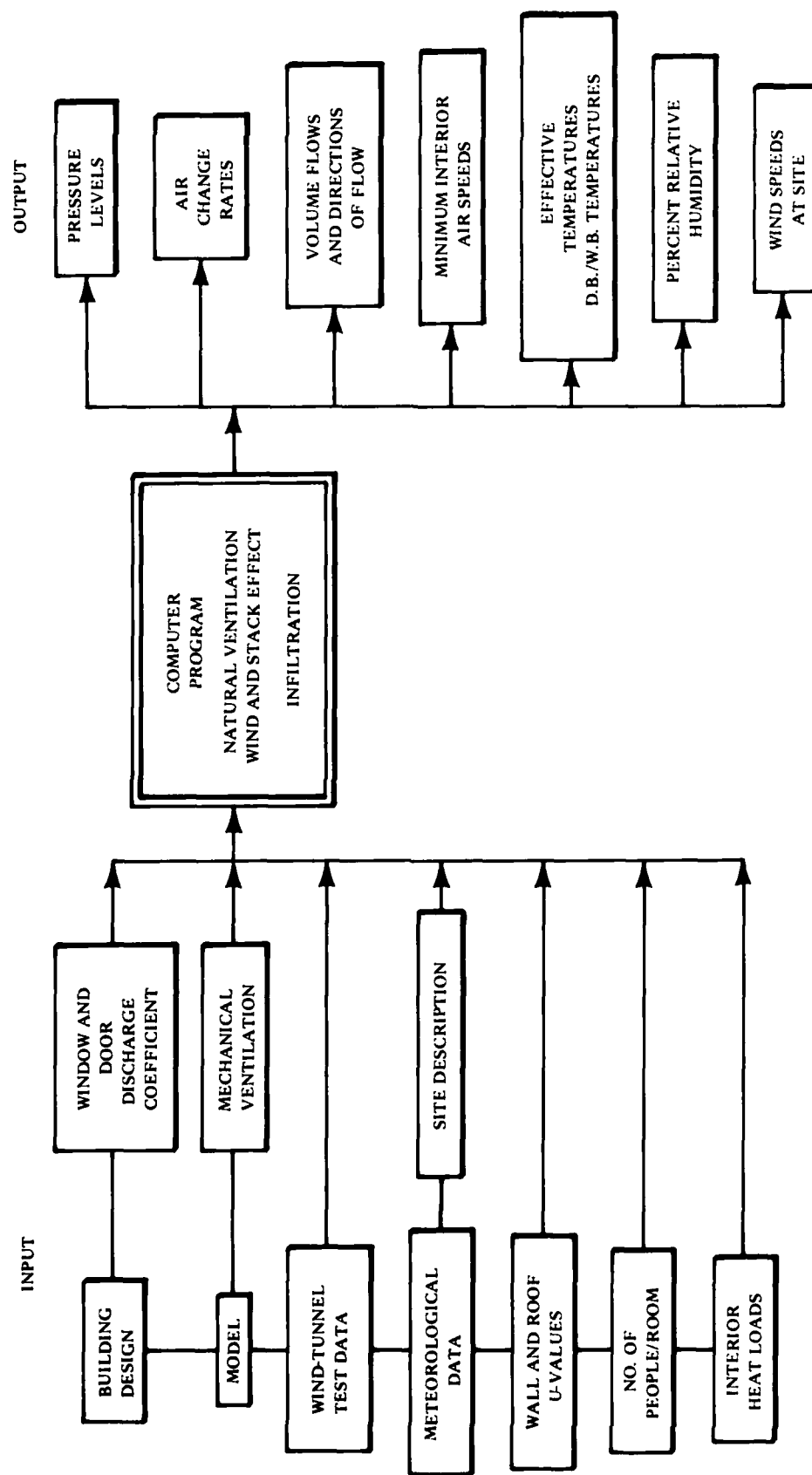


Figure 1.1. Computer program.

## Chapter 2

### WEATHER

#### 2.1 WEATHER DATA ACQUISITION

Weather data information on surface winds and psychrometric summaries for a region can be obtained from:

- (1) Local weather stations
- (2) Naval Weather Service Detachment, Asheville, N.C.

Yearly weather data are derived from daily observations and are presented by month and year for all years combined. Examples of received data are shown in Appendix A.

#### 2.2 WIND EFFECTS ON BUILDINGS

Wind incidence on a building causes positive pressures on the windward faces and negative pressures (or suctions) on the leeward faces. As a result, a pressure difference is generated which gives rise to a basically horizontal movement of air in through openings or cracks in the windward side of the building and out through similar openings in the other sides.

##### 2.2.1 Nature of Wind

In assessing the effects of wind on a building, it is important to consider the characteristic nature of the wind. The wind is turbulent, and its mean speed varies with height. Turbulent characteristics and the vertical profiles of wind velocity vary with the stability of the atmosphere. Local topographical features, such as roughness of terrain over which the wind is passing, hills, and valleys, can also affect wind profiles. Vertical profiles of mean wind speed for boundary layers are approximated by taking the wind speed to be proportional to the height raised to some power - a "power-law" variation (Ref 2.1). The simple expression which is used extensively has the form

$$\frac{U_r}{U_m} = K z^a \quad (2.1)$$

where  $U_m$  = wind speed from local meteorological office

$U_r$  = wind speed as specified height

$K$  = terrain factor

$a$  = terrain exponent

$z$  = the specified height

For different types of terrain, Equation 2.1 describes the wind speed variation as a power-law profile. The wind speed ( $U_m$ ) is measured by the local meteorological office, and is measured for an equivalent height of 10 meters (33 feet) in open countryside.

Equation 2.1 relates the wind speed at any other height ( $U_r$ ) and for any of the types of terrain to the wind speed,  $U_m$ . Factors for determining mean wind speed at different heights and for different types of terrain are given in Table 2.1.

Table 2.1 Factors for Determining Mean Wind Speed at Different Heights and for Different Types of Terrain From Meteorological Office Wind Speed,  $U_m$ , Measured at 10 Meters in Open Country

Terrain	K	a
Open flat country	0.68	0.17
Country with scattered windbreaks	0.52	0.20
Urban	0.40	0.25
City	0.31	0.33

For an urban site and a building height of 20 feet, the wind velocity at the roof of the building is calculated as follows.

$$U_{20} = (0.40)(20)^{0.25} U_m$$

$$U_{20} = 0.85 U_m$$

Hence, the roof top velocity (or local velocity,  $U_r$ ) at an urban site is 15% less than the measured meteorological wind velocity in an open site for the same gradient velocity.

For a potential building site, when the type of the terrain is established (open flat country, urban, etc.) the appropriate corresponding values of K, and desired height, z, are used as input data to the program and the expected wind speed at the site is calculated and used to calculate wind pressures on building surfaces and expected interior air velocities.

### 2.2.2 Wind Pressures

The distribution of wind pressure around a building depends very closely upon the local variation in wind velocity which the building produces. In accordance with the elementary pressure-velocity relationship (Ref 2.2)

$$P - P_o = \frac{\rho U_o^2}{2} - \frac{\rho U^2}{2} \quad (2.2)$$

Evidently, as the velocity (U) increases above its initial value ( $U_o$ ), the pressure (P) decreases and vice versa in proportion to the density ( $\rho$ ) and the square of the velocity.

For convenience the pressure distribution around the building is represented by a dimensionless pressure coefficient ( $C_p$ ). The wind pressure or velocity pressure ( $P_w$ ) may, therefore, be represented by,

$$P_w = C_p \frac{\rho U_r^2}{2} \quad (2.3)$$

where  $P_w$  = wind pressure, Pa (pascals)

$\rho$  = air density, kg/m<sup>3</sup>

$U_r$  = wind speed at site (usually taken at roof level), m/sec

Pressure coefficients applicable to simple building shapes are available (Ref 2.3). For residential and commercial buildings the expected pressure coefficients are given for different wind incidence angles in Appendix B and References 2.1, 2.2, 2.4, and 2.5.

The computer program will calculate the wind pressure on a building surface when the proper pressure coefficients are chosen and used as input data to the program. This wind pressure in turn is used to calculate the volume flow rates in each building room (or node).

To determine the pressure coefficients applicable to the surfaces of complex buildings, it is necessary to use wind tunnel testing techniques.

### 2.2.3 Stack Effect

The difference in temperature and hence in density between air inside a building and air outside causes a movement of air vertically through the building via such openings as lift shafts and stairwells. This temperature-motivated transfer of air is called "stack effects."

The pressure differences due to stack effects may be calculated, and are given in Reference 2.6 as

$$P = 3462 h \left( \frac{1}{T_o} - \frac{1}{T} \right) \quad (2.4)$$

where  $P$  = pressure difference, Pa

$h$  = vertical distance between inlet and outlet openings, m

$T_o$  = external absolute temperature, °K

$T$  = internal absolute temperature, °K

If the temperature difference between inside and outside the building is 20°C and the story height is 3 meters, then the pressure difference will be 2.6 Pascals per floor. Hence, for a 10-story building, the pressure that will be added to the wind pressure outside is:

9 x 2.6 Pa      to all ground floor wind pressures

8 x 2.6 Pa      to first floor wind pressures

0 x 2.6 Pa      to ninth floor wind pressures

For most natural ventilation cooling of building applications, the "stack effect" is omitted. The "stack effect" is included in the computer program, and it is an option to the user. If it is used, then the pressures printed at the end of the program will be essentially incorrect; however, the air volume flow rates and directions of flow will be correct.

### 2.3 REFERENCES

2.1 A. G. Davenport. 1963 proceedings of the Conference on Wind Effects on Buildings and Structures, vol 1. HMSO, 1965.

2.2 S. Goldstein. Modern developments in fluid dynamics. England, Oxford University Press, 1938.

2.3 British Standard CP3, Chapter V, part 2, 1972.

2.4 University of Sydney. Wind generated natural ventilation of housing for thermal comfort in hot climates, by R. M. Aynsley. Sydney, Australia.

2.5 National Science Foundation. Grants ENG72-04260-A01 and ENG76-03035: Wind pressures on buildings, by R. W. Akins and J. E. Cermak. Fall 1976.

2.6 Department of Health and Social Security. BSRIA Report: Natural ventilation in hospital buildings. 1976.

## Chapter 3

### AIR FLOW CHARACTERISTICS

#### 3.1 EQUATIONS

The rate of air flow through a building is determined by the air flow from high-pressure to low-pressure regions via available paths and the resistance offered by the flow paths, such as doors, windows, partitions, etc.

The general equation relating the air flow ( $Q$ ) through a component with a pressure differential ( $\Delta P$ ) across it (Ref 3.1) is expressed by an equation of the form

$$Q = K_i (\Delta P)^{1/N} \quad (3.1)$$

where  $Q$  = flow rate

$K_i$  = leakage coefficient of the component

$\Delta P$  = pressure difference between two rooms (or nodes)

$N$  = exponent that depends on the nature of the flow through the opening and ranges between 1 and 2

To permit use of this generalized equation for specific situations, the following alternatives may be considered.

For the air leakage through closed doors or windows, Equation 3.1 is often expressed as

$$Q = C \ell (\Delta P)^{1/N} \quad (3.2)$$

where  $Q$  = flow rate,  $m^3/sec$

$C$  = crack coefficient per unit length of sash crack,  
 $m^3/sec/m$  at 1 Pa

$\ell$  = crack length,  $m$

The value of  $N$  varies between 1 and 2. For very small openings (cracks), the flow is laminar, and  $N$  approaches 1. As the size of the opening is increased, the flow becomes turbulent and  $N$  approaches 2. Values of  $C$  and  $N$  are given in Appendix C, Table C-2.

For open windows or doors, the flow rate is comparable to that through a thin-plate orifice with flow in the turbulent region and a discharge coefficient  $C_d$  of 0.65, Equation 3.1 now becomes

$$Q = 1.27 C_d A_i (\Delta P)^{1/2}$$

or

$$Q = 0.827 A_i (\Delta P)^{1/2} \quad (3.3)$$

where 0.827 is the leakage coefficient ( $\text{m/s} - (\text{Pa})^{1/2}$ ), and  $A_i$  is the area of the orifice ( $\text{m}^2$ ). For different values of discharge coefficient,  $C_d$ , see Appendix C, Table C-2.

For air flows through components in parallel, as shown in Figure 3.2, the same pressure differential acts across them all, and the total air flow rate is given by

$$Q = 0.827 (\Delta P)^{1/2} (A_1 + A_2 + \dots) \quad (3.4)$$

where  $A_1$ ,  $A_2$ , etc., are the respective orifice areas of the components.

If the components are in series, the effective area of an orifice in Equation 3.3 is given by (Ref 3.2)

$$\frac{1}{A_i^2} = \frac{1}{A_1^2} + \frac{1}{A_2^2}$$

The total effective area of the orifice is therefore always less than the area of either of the two separate components. Figure 3.1 (Ref 3.1) shows that when the area of one set of openings is more than four times the area of the other set, then only the area of the smaller openings needs to be considered.

Examples of how to combine rooms/components are given in Figure 3.2 (Ref 3.3). In Appendix C, Tables C-1 (Ref 2.4) and C-2 (Ref 2.6) give a summary of air leakage data for building components taken from various sources.

## 3.2 REFERENCES

- 3.1 ASRAE. Handbook of fundamentals, chapter 25. 1967.
- 3.2 B.R.E.D. Principles of natural ventilation. Feb 1978.
- 3.3 Department of Health and Social Security. BSRIA Report: Natural ventilation in hospital buildings. 1976.

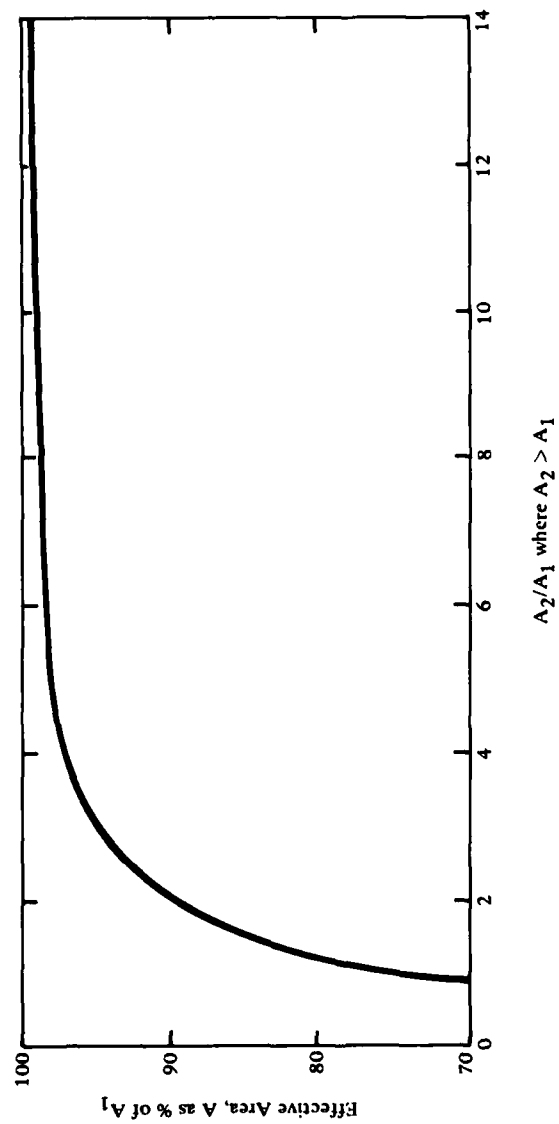
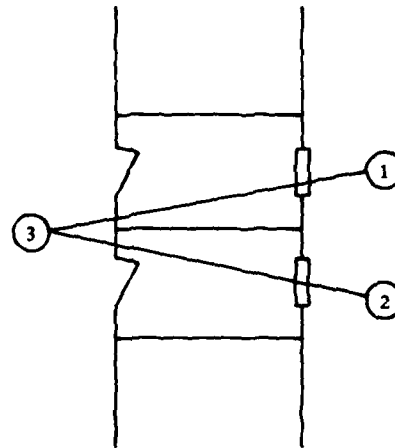


Figure 3.1. Effective area of openings in series.

### Option A

Conditions: no mechanical ventilation in rooms



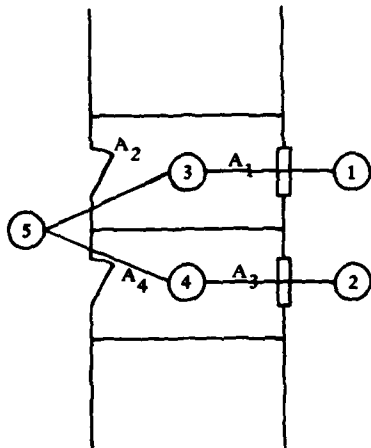
from node 1 to node 3

$$A_w = \frac{A_1 A_2}{(A_1^2 + A_2^2)^{1/2}}$$

from node 2 to node 3

$$A_w = \frac{A_2 A_4}{(A_2^2 + A_4^2)^{1/2}}$$

### Standard Method

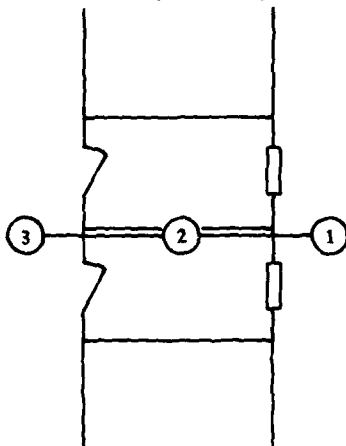


from node 1 to node 3  $A = A_1$

from node 3 to node 5  $A = A_2$ , etc.

### Option B

Conditions:  $A_1 = A_3$  and  $A_2 = A_4$   
the mechanical ventilation in each room is equal; wind pressures equal



from node 1 to node 2

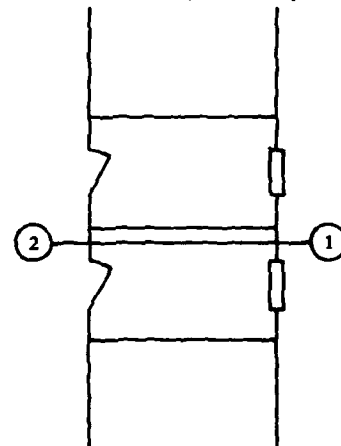
$$A = A_1 + A_3$$

from node 2 to node 3

$$A = A_2 + A_4$$

### Option C

Conditions: no mechanical ventilation in rooms; wind pressures equal



from node 1 to node 2

$$A_w = \frac{A_1 A_2}{(A_1^2 + A_2^2)^{1/2}} + \frac{A_3 A_4}{(A_3^2 + A_4^2)^{1/2}}$$

Figure 3.2. Examples of how to combine rooms or components.

## Chapter 4

### EFFECTIVE TEMPERATURE

#### 4.1 INTRODUCTION

A physiological measurement combining the effects of temperature, humidity, and air movement is called the effective temperature (ET) scale. New comfort limits by ASHRAE Standard 55-74 are for ET\* between 72°F and 78°F with maximum relative humidity of 80% for the upper limit (Ref 4.1).

The effective temperature that results inside a building depends on many factors, including:

1. Ventilation air flow rate ( $Q$ ) through the building
2. Dry-bulb temperature ( $T_{DB}$ ) and wet-bulb temperature ( $T_{WB}$ ) of ambient air
3. Metabolic heat generation rate of occupants ( $Q_{occ}$ )
4. Heat transferred through the envelope of the structure
5. Interior heat loads ( $Q_s$ ), such as direct sunlight, electric light bulbs, etc.
6. Air flow pattern inside the building, etc.

Heat transferred through the building envelope is assumed steady state. Air within the building is assumed to be uniformly distributed such that no air stratification or temperature variation occurs. The building effective temperature is then assumed to be a function of the following:

$$ET = f(Q_s, Q_{occ}, Q, T_{DB}, T_{WB}) \quad (4.1)$$

Using the building configuration, the hourly data, and the number of occupants, an example of the average daily effective temperature inside each room of the building due to varying ambient weather is plotted against time as shown in Figure 4.1.

## 4.2 OCCUPANT METABOLIC HEAT

The average metabolic rates for sedentary activity levels as functions of age and sex for the most recent census of the U.S population are given in the 1978 ASHRAE Applications Handbook; Table 4.1 and subsequent equations were developed by GATEX (Ref 4.2) using these data.

Table 4.1. Sedentary Metabolic Rates as a Function of Age and Sex

Age	Percent of Population <sup>a</sup>		Metabolic Heat (Btu/hr)	
	Male	Female	Male	Female
75 and over	1.5	2.2	310	200
70 to 74	1.1	1.5	320	210
65 to 69	1.5	1.8	350	230
60 to 64	2	2.3	360	235
55 to 59	2.3	2.7	370	240
50 to 54	2.6	2.8	375	245
45 to 49	2.9	3.1	380	250
40 to 44	2.9	3	395	250
35 to 39	2.7	2.9	400	250
30 to 34	2.8	2.9	400	250
25 to 29	3.3	3.3	400	250
20 to 24	3.9	4.2	405	250
15 to 19	4.7	4.6	400	260
10 to 14	5.3	5	275	250
5 to 9	5	4.8	200	200
Under 5	4.3	4.1	150	150
Total	48.8	51.2	--	--

<sup>a</sup>"Social Indicators," 1973, U.S. Dept. of Commerce

The polynomial expressions for metabolic heat generation (Ref 4.3) are as follows:

$$Q_{\text{occ,total}} = a (ET)^2 + b (ET) + c \quad (4.2)$$

$$Q_{\text{occ,sensible}} = A (T_{\text{DBB}})^2 + B (T_{\text{DBB}}) + C$$

where  $T_{\text{DBB}}$  = the dry bulb temperature of the building air

1.  $a = 0; b = 1.482; c = 514$ , for  $50^\circ \leq ET \leq 87^\circ F$
2.  $a = -1.508; b = 259.7; c = -10,795.2$ , for  $87^\circ < ET \leq 102^\circ F$
3.  $a = 0; b = 0; c = 0$ , for  $ET > 102^\circ F$
4.  $A = -0.06875; B = 1.625; C = 523$ , for  $T_{DBB} \geq 50^\circ F$

and

$$Q_{occ,total} = Q_{occ,sensible} + Q_{occ,latent} \quad (4.3)$$

Equations 4.2 and 4.3 have been applied and proved for only healthy male subjects in the age group of 18 to 24 years. For this study an "average person," whose metabolic heat rate is the weight average that has been created using the following equation:

$$Q_{average\ person} = \frac{(\% \text{ of males}) \times (\text{Btu/hr male}) + (\% \text{ of females}) \times (\text{Btu/hr female})}{100} \\ = 281.32 \text{ Btu/hr} \quad (4.4)$$

This is 70% of the value given in the table for males between 20 and 24 years. This weight average is used in the program to give the percent of "average" people who will be comfortable within prescribed temperature limits. Using the above equations and data from Ref 4.4 (pages 6 to 8, Tables 2 and 3) the following equations were generated for calculating occupant metabolic heat:

$$Q_{occ,total} = 0.413[a(ET)^2 + b(ET) + c] [N + 1.091 \sum_{i=1}^N U_i^{0.6}] \quad (4.5)$$

$$Q_{occ,sensible} = 0.413[A(T_{DBB})^2 + B(T_{DBB}) + C] [N + 1.091 \sum_{i=1}^N U_i^{0.6}]$$

where  $N$  = number of occupants

$U_i$  = air velocity felt by occupant  $i$

The effective temperature (ET) of the building air can be calculated as

$$ET = \frac{107.5(T_{DBB}) - 45.2(T_{WBB})}{T_{DBB} - T_{WBB} + 62.3} \quad (4.6)$$

where  $T_{DBB}$  = dry-bulb temperature of building air

$T_{WBB}$  = wet-bulb temperature of building air

#### 4.3 BUILDING HEAT BALANCE

Sensible and latent heat loads and ventilating air are introduced into the building, air is exhausted out of the building and energy is lost (see Figure 4.2).

The following assumptions are made (Ref 4.2):

1. The air within the building is completely and instantaneously mixed.
2. The film heat transfer coefficients are constant for any one boundary surface.
3. The radiative energy transfer within the building can be neglected.
4. The condition of the air exhausted from the building is the condition of the building atmosphere.
5. The thermal and physical properties of the structural materials and of air are not temperature-dependent.
6. The incident solar radiation is absorbed on the outer surface of the boundaries and appears as conducted energy or is transmitted into the building and is considered an instantaneous load along with other internal loads.
7. The thermal loads and the psychrometric states of the inlet and exhaust air are constant over short time intervals.

A heat balance of the building volume yields the following:

$$\text{Sensible Heat Gain} = Q_{\text{occ,sensible}} + (K_W \times F_W + K_R \times F_R) \cdot (T_{DB} - T_{DBB})$$

$$\text{Latent Heat Gain} = Q_{\text{occ,latent}}$$

$$\text{Sensible Heat Loss} = 60 \times C_p \times \rho \times Q \times (T_{DB} - T_{DBB}) \quad (4.7)$$

$$\text{Latent Heat Loss} = 0.625 \times 10^{-5} \times \rho \times Q \times (W_B - W)$$

where  $\rho$  = density of leaving air

$Q$  = flow rate

$K_W$  &  $K_R$  = heat transfer coefficient for building wall and building roof

$F_W$  &  $F_R$  = total external wall or roof surface area

$W_B$  = humidity ratio of building air

$W$  = humidity ratio of outside air

$C_p$  = specific heat of air

Since we assume that the building is in thermal equilibrium at the end of each time interval,

$$\text{Heat Gain} = \text{Heat Loss} \quad (4.8)$$

Therefore, using Equations 4.7 and 4.8, and solving  $Q_{\text{occ,sensible}}$  and  $Q_{\text{occ,latent}}$ , the following relations are obtained,

$$Q_{\text{occ,sensible}} = [60 \times C_p \times \rho \times Q + (K_W \times F_W + K_R \times F_R)] \cdot (T_{DBB} - T_{DB}) \quad (4.9)$$

and

$$Q_{\text{occ,latent}} = 0.625 \times 10^{-5} \times \rho \times L(W_B - W) \quad (4.10)$$

Using Equations 4.2 through 4.10 the following equation is obtained:

$$T_{DBB} = \frac{-(\bar{N} \times B + Z) \pm \sqrt{(\bar{N} \times B - Z)^2 - 4(N \times A) Z(T_{DBT}) + \bar{N} \times C}}{2 \bar{N} \times A} \quad (4.11)$$

where

$$Z = [0.000355 \times (PB) \times Q + (K_W \times F_W) + (K_R \times K_R)]$$

$$\bar{N} = 0.413 \left[ N + 1.091 \sum_{i=1}^N U_i^{0.6} \right]$$

and

$$PB = \text{barometric pressure}$$

Once the flow rate, Q, is established, the resulting interior effective temperature can be calculated at each room and the percent of people who will feel comfortable is given along with the percent of relative humidity.

#### 4.4 REFERENCES

- 4.1 ASHRAE. Handbook of Fundamentals. 1977, pp 8.1-8.36.
- 4.2 GATEX. CARD Report A1-11 (1713): Adequacy of wind ventilation in upgraded shelters. Jun 1980.
- 4.3 F. C. Houghten. "Heat and moisture from the human body and their relation to air conditioning problems," ASHVE, Transaction, vol 35, 1929.
- 4.4 ASHRAE Handbook of Fundamentals, Chapter 8, Physiological principles, comfort and health. 1977.

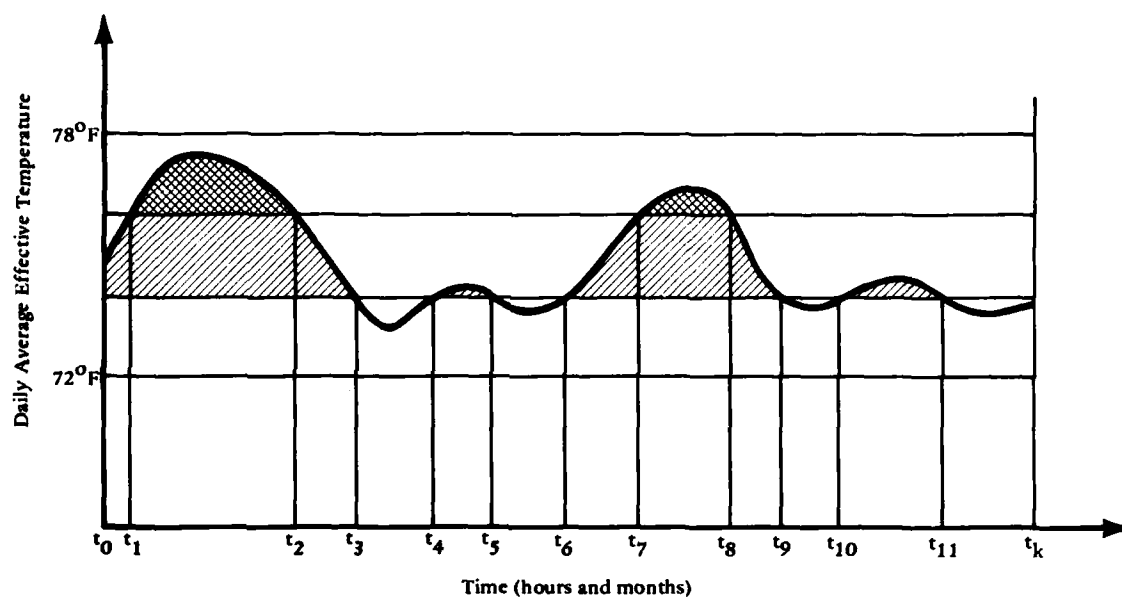


Figure 4.1. Variation of building (one room) daily average effective temperature with time.

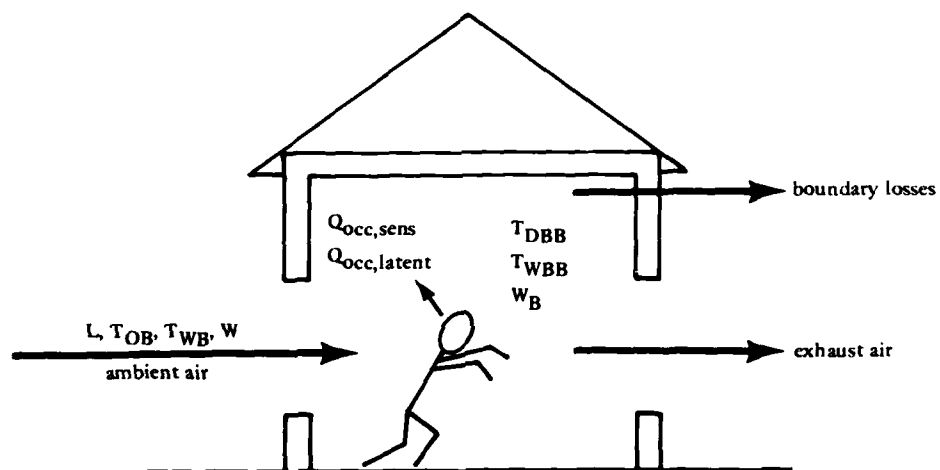


Figure 4.2. Typical heat balance required for buildings.

## Chapter 5

### COMPUTER SIMULATION OF NATURAL VENTILATION COOLING OF BUILDINGS

#### 5.1 ASSUMPTIONS, LIMITATIONS, AND BACKGROUND PROGRAM

A brief summary of assumptions, limitations, and formulation of the "CRKFLO" computer program (Ref 5.1) is presented in this chapter.

1. Net air supplied (or extracted) by mechanical ventilation system is assumed to be constant and independent of building pressures.
2. Each room (or node) of the building is considered to be at a uniform pressure throughout the room.
3. If very large openings are considered, difficulty of convergence may be experienced. This restriction can be overcome by redesigning the node network. This problem occurs if pressure of less than  $10^{-6}$  Pascal is encountered across the component, so the resultant flow will probably be insignificant.
4. The average interior air speed is calculated by using air flow rate divided by cross-sectional area of room (node).
5. The average dry-bulb and wet-bulb temperature of each node is a function of incoming air conditions at the room and represents conditions of air leaving the room (node).
6. There is no heat transfer through partitions.

A network of air flow paths comprises the nodes and their associated interconnections, which in many ways is analogous to flow through electric circuits (Ref 5.1). The solutions of these are in general complicated and require trial solutions in which the elementary circuits are balanced in turn until all conditions for the flow are satisfied. Three basic conditions must be satisfied in any network:

1. The algebraic sum of the pressure drops around each circuit must be zero.
2. Flow into each node must equal the flow out of the node.
3. The equation relating the pressure difference and flow for each interconnection must be satisfied.

The solution to the equation,

$$Q = K (\Delta P)^{1/N} \quad (5.1)$$

is obtained by an iterative process (Ref 5.2), in which during each successive cycle corrections are made to the values of the pressure heads at the nodes (or rooms) for which pressures were not specified. The source of the corrective term is as follows:

For any interconnection

$$\Delta P = \Delta P_0 + CR \quad (5.2)$$

where  $\Delta P$  = correct pressure difference

$\Delta P_0$  = assumed pressure difference

CR = correction

Then, for each interconnection

$$Q = K (\Delta P_0 + CR)^{1/N}$$

$$Q = K (\Delta P_0^{1/N} + \frac{1}{N} \Delta P_0^{(1/N - 1)} \cdot CR + \dots) \quad (5.3)$$

By expanding the Taylor series of Equation 5.3 to include the second order differential, the equation becomes

$$Q = K \cdot \Delta P_0^{1/N} + \frac{K}{N} \Delta P_0^{(1/N - 1)} \cdot CR + \frac{K}{N} \frac{(1/N - 1)}{2!} \cdot \Delta P_0^{(1/N - 2)} \cdot CR^2 \quad (5.4)$$

For all the interconnections to a room (node),

$$Q = \sum K \Delta P_0^{1/N} = \sum K \Delta P_0^{1/N} + CR \cdot \frac{\sum K}{N} \Delta P_0^{(1/N - 1)} + CR^2 \cdot \frac{\sum K}{N} \frac{(1/N - 1)}{2} \Delta P_0^{(1/N - 2)} = 0 \quad (5.5)$$

CR has been taken out of the summation since it is the same for all the interconnections around the room. The quadratic solution for CR becomes:

$$CR = \frac{\sum K}{N} \Delta P_0^{(1/N-1)} \pm \sqrt{\frac{\sum K}{N} \Delta P_0^{(1/N-1)^2 - 4 \cdot (\sum K \Delta P_0^{1/N}) \cdot (\frac{\sum K}{N} (1/N-1) \Delta P^{(1/N-2)})} {2 \cdot \frac{\sum K}{N} \frac{(1/N-1)}{2} \cdot \Delta P^{(1/N-2)}}}$$

. . . . . (5.6)

The use of this correction factor yields a fast convergence to the solution.

## 5.2 NETWORK REPRESENTATION OF BUILDING

A plan view of the building under consideration is obtained, and each room or compartment represents a node. Outside wind pressure areas are also represented by nodes (Ref 5.1). Each set of nodes is interconnected by air flow paths (see Figure 5.1). It is assumed that substantially uniform pressure conditions prevail at each node. The interconnections correspond to impedance to the air flow such as windows and doors. A knowledge of the air flow characteristics is required for each door and window contained in the network.

The number of exterior nodes is designated as MH, and MT-MH nodes represent rooms and corridors inside the building. Pressures for the external nodes must be specified and these pressures will represent a combination of wind pressures and buoyancy pressures (stack effect).

The nodes are numbered from 1 in ascending order, starting with the nodes for which a known pressure will be specified (see Figure 5.1); there will be MH of these. The numbering for the internal nodes (rooms and corridors) continues in sequence, starting at MH+1 through to MT, where MT is the last node.

R denotes the number of each node connected to P taken in numerically ascending order, and is only defined if R>P; otherwise, it is zero (see Figure 5.1). K and N are the characteristic constants for each particular interconnection. Zero terminates the sequence of interconnections to each particular node P and must appear even if no interconnections are listed.

To convey the network shape to the computer, the data must be input in a strict order. The following is an example of the generation of a network of Figure 5.1.

<u>Listing</u>	<u>Notes</u>
P = 1	
R = 4	R > P
K <sub>14</sub> N <sub>14</sub>	
R = 0	R = 0 terminates the sequence.

$P = 2$   
 $R = 5$   
 $K_{15} = 0$       $N_{15}$

For input area, A, the value of K is computed by the program.

$P = 3$   
 $R = 6$   
 $K_{36} = 0$       $N_{36}$

MH = 1, 2, and 3 are the exterior nodes with known pressures.

$P = 4$   
 $R = 5$   
 $K_{45} = 6$       $N_{45}$   
 $K_{46} = 0$       $N_{46}$

From node 4 to node 1, R is less than P (1 < 4), thus R = 0. This is to avoid listing interconnections twice.

$P = 5$   
 $R = 6$   
 $K_{56} = 0$       $N_{56}$

MH+1 = 4, 5, and 6 are the interior nodes with the unknown pressures.

$P = 6$   
 $R = 0$

Pressures are to be specified at nodes 1, 2, and 3.

When mechanical ventilation is present in a room the volume flow rate in  $m^3/s$  is specified and used as input data to the computer program. Additional input data consists of room volume and length. The program calculates pressures and pressure differences at and between nodes, volume flow rate, and direction air changes per hour at each node, and interior air speed. The study of direction of smoke in the event of a fire in the room can be predicted by the direction of the flow in or out of the room.

### 5.3 REFERENCES

5.1 Department of Health and Social Security. BSRIA Report: Natural ventilation in hospital buildings. 1976.

5.2 G. T. Tamura. "Computer analysis of smoke movement in tall buildings," ASHRAE Transactions, 1969, 75, II, 81.

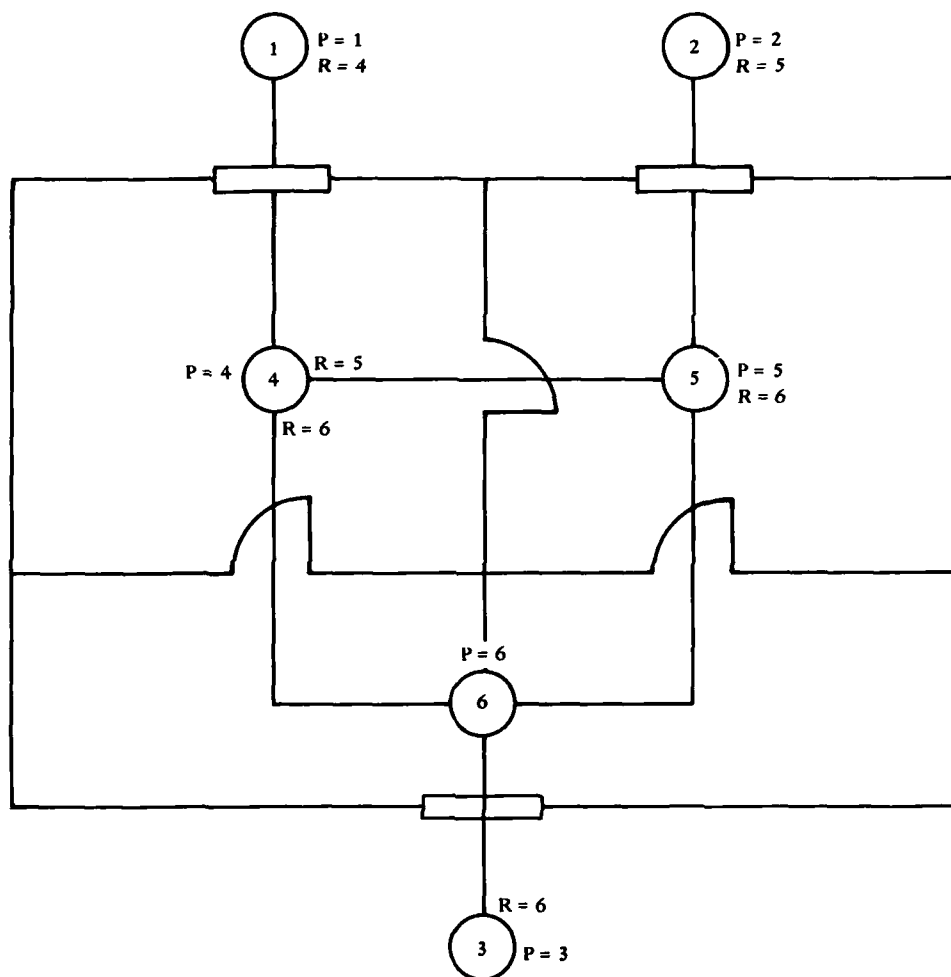


Figure 5.1. Plan view of building. Pressure coefficient must be specified at external nodes 1, 2, and 3.

## Chapter 6

### COMPUTER PROGRAM

This program is stored at CDC KWA, Sunnyvale, Calif., on PUBLIC READ TAPE: VSN = PN2339, and it is written in FORTRAN IV computer language. The program consists of two main routines; Routine Flow calculates air flow through the building, and Routine Air estimates temperatures based on results of Flow routine.

#### 6.1 COMPUTER PROGRAM NOMENCLATURE

The following explains each data element in order.

AKW	Total heat transfer coefficient of exterior wall, Btu/hr-ft <sup>2</sup>
AKR	Total heat transfer coefficient of roof, Btu/hr-ft <sup>2</sup>
ALF	Exponent for calculating local velocity
AR	Area of inlets, ft <sup>2</sup> (if "stack effect" used, divide calculated area by 0.827)
CP	Pressure coefficient
CQ	Flow equation exponent
DBT	Dry-bulb outside temperature, °F
EL	Length of room, ft
FN	Number of specific floor
FR	Roof area, ft <sup>2</sup>
FW	Exterior wall area, ft <sup>2</sup>
HB	Height of building, ft
HS	Initial estimate of pressure at each internal node, Pascal
ITITL	Name of case

ITLIM	Maximum number of matrix inversions allowed
KM	Terrain constant
M	Flag, equal to zero means no "stack effect"; equal to one means "stack effect"
MH	Number of nodes at which pressure is specified
MP	Maximum number of interconnections at any node
MT	Number of nodes
NAR	Number of interconnections for flow equation constants, $\leq 21$
NCS	Maximum number of iterations allowed
NF	Number of floors, including ground floor
NUM	Number of occupants
P	Node (room)
PB	Barometric pressure x 100, in. Hg
Q	Mechanical ventilation at each internal node, $\text{m}^3/\text{sec}$
QL	Electric heat load, kW
QSOL	Algebraic sum of other heat loads, Btu/hr
R	Node (to)
TI	Absolute interior temperature, $^{\circ}\text{F}$ , (for $M = 1$ , "stack effect")
TO	Absolute exterior temperature, $^{\circ}\text{F}$ , (for $M = 1$ , "stack effect")
ULT	Convergence criterion for sum of flow errors
UM	Meteorological wind speed, knots or mph
VOL	Room volume, $\text{ft}^3$
WBT	Outside wet-bulb temperature, $^{\circ}\text{F}$
WD	Wind directions in degrees
WFLAG	= 0 meteorological wind speed in mph = 1. meteorological wind speed in knots

## 6.2 ORDER OF INPUT DATA

### DECK SET-UP

```

NAME,PRIORITY,TIME,STK WA.
USER,USER NAME,PASSWORD,KWA.
CHARGE,CHARGE#,PROJECT#.
COPYCR,INPUT,TAPE5.
COPYCR,INPUT,TAPE7.
(JCL) REQUEST,TAPE,VSN=PN2339,D=PE,UN=L6023GS.
COPYBF,TAPE,PROGR.
REWIND,PROGR.
UNLOAD,TAPE.
FTN,R=3,L=0,I=PROGR.
ATTACH,CELLIB/UN=L5107GS.
LDSET,PRESET=ZERO,LIB=CELLIB.
LGO,PL=100000.
ROUTE,PLOT,UN=L0601GS,ST=WCZ,DC=PU.
/*EOR
(TAPE5) WEATHER DATA (HOUR,DRY BLB,WET BLB,BAROM.PRESS.,MONTH)
ON LAST RECORD HOUR=99
FORMAT (I5,3F 10.1,1XA3).
/*EOR
(TAPE7) WIND SPEED (ONE VALUE/RECORD)
DATA ON LAST RECORD UM=999
/*EOR
TITLE (≤80 CHARACTERS) IF EMPTY=END OF JOB
NF,FN
HB,ALF,KM,M
NAR
(AR(I),I=1,NAR)
MT,MP,HS
P
R REPEAT AS OFTEN AS NECESSARY
CQ IF R ≠ 0

MH,ULT
NCS,ITLIM

IF M ≠ 0
TI,TO
Q(I) I=MH+1,MT
EL(I) I=MH+1,MT
QL(I) I=MH+1,MT
QSOL(I) I=MH+1,MT
AKW(I) I=MH+1,MT
AKR(I) I=MH+1,MT
FW(I) I=MH+1,MT
FR(I) I=MH+1,MT
VOL(I) I=MH+1,MT
NUM(I) I=MH+1,MT
WFLAG

```

WD,(CP(I),I=1,MH) REPEAT THIS RECORD FOR WIND DIRECTION.  
 LAST RECORD WD=999  
 REPEAT FROM TITLE RECORD ON

/\*EOR

END OF FILE=SPECIAL CARD IF CARD-INPUT  
 =/\*EOR IF TERMINAL TYPE IN.

### 6.3 COMPUTER INPUT AND OUTPUT EXAMPLE

Using the network representation of a single story on-grade  
 (Figure 5.1) building at a zero degree incidence to long walls, (Ref 2.4)  
 Appendix B, Table B-2, the input and output data are as follows:

#### EXAMPLE VENTILATION, ONE STORY BLDG, GAMA 0.5

```
( 1) **** CARD LISTING **** FRI, SEP 24 1982 AT 13:15:41
( 2) REMOTE CDC
( 3) SOPHIA,P4,T200,STKWA.
( 4) USER,L6023GS,ACE LPAS,KWA.
( 5) CHARGE,M4821DS,314630R97.
( 6) COPY CR,INPUT,TAPE5.
( 7) COPY CR,INPUT,TAPE7.
( 8) REQUEST,TAPE,VSU=PN2339,PC=M,D=PE.
( 9) COPY BF,TAPE,SOPHIA.
(10) REMIND,SOPHIA.
(11) UNLOAD,TAPE.
(12) FTYN,R=3,I=SOPHIA.
(13) ATTACH,CELLIB/UN=L5107GS.
(14) LOSE 1,PRESET=ZERO,LIB=CELLIB.
(15) LGO,PL=10000.
(16) ROUTE,PL0T,JN=L0F01GS,ST=WC?,OC=PU.
(17) EXIT.
(18) EXIT.
(19) FTYN,R=3,I=SOPHIA,L=1.
(20) /*EOR
(21) 1 75.7 70.0 29.02 JUL
(22) 4 75.2 70.0 29.02 JUL
(23) 7 76.0 70.0 29.02 JUL
(24) 10 75.0 71.0 29.02 JUL
(25) 13 80.2 72.0 29.02 JUL
(26) 16 75.7 72.0 29.02 JUL
(27) 19 77.5 71.0 29.02 JUL
(28) 22 75.3 70.0 29.02 JUL
(29) 99
(30) /*EOR
(31) 10
(32) 999
(33) /*EOR
(34) CAGE 3 / PARTITION, AR=80 PERCENT
(35) 1 0
(36) 10 0.20 0.40 0
(37) 0
(38) 206 256 112 21 256 256
(39) 3 1.1
(40) 1
(41) 4
(42) 0.5
(43) 0
(44) 2
(45) 5
(46) 0.5
(47) 0
(48) 3
(49) 6
(50) 0.5
(51) 0
(52) 4
(53) 5
(54) 0.5
(55) 6
(56) 0.5
(57) 0
```

```

( 58) 5
( 59) 6
( 60) 0.5
( 61) 0
( 62) 6
( 63) 0
( 64) 3 0.001
( 65) 10 10
( 66) 0 0 0
( 67) 20 20 13
( 68) 0 0 0
( 69) 0 0 0
( 70) 0.00 0.09 0.09
( 71) 0.00 3.03 0.05
( 72) 234 234 276
( 73) 900 900 900
( 74) 6400 6400 6400
( 75) 0 5 5
( 76) 0
( 77) 0 0.5 0.6 0
( 78) 9.99 0. 0. 0.
( 79)

```

CAS 3 / PARTITION. AR=49 0.40 VT

JUL 13 11 CLOCK

# PREDICTION OF VENTILATION RATES

WIND SPEED AT SITE 2.45 METER/SEC. AT TOWER 4.47 METER/SEC = 10.000 MILES/HR

WIND DIRECTION 0.00

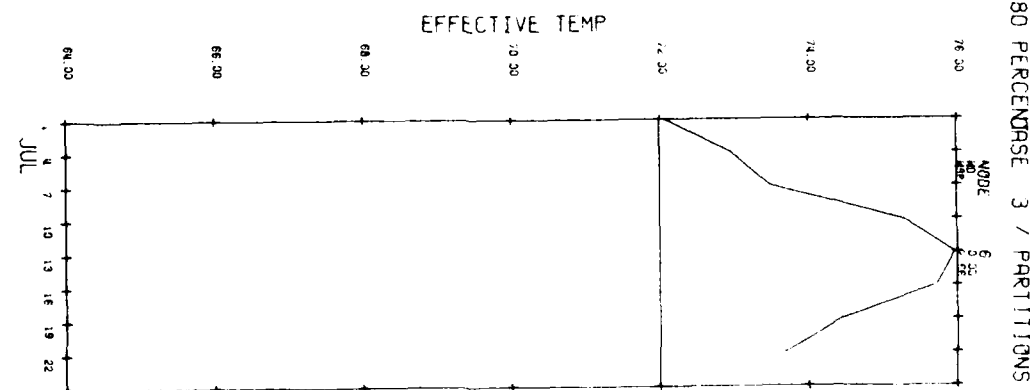
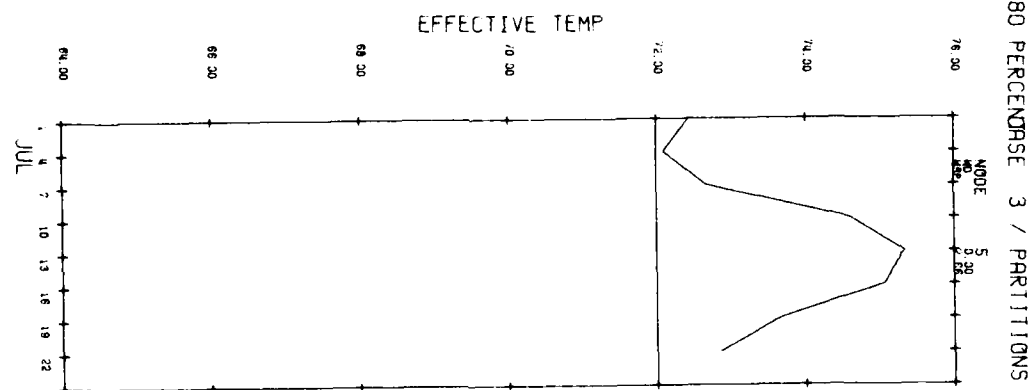
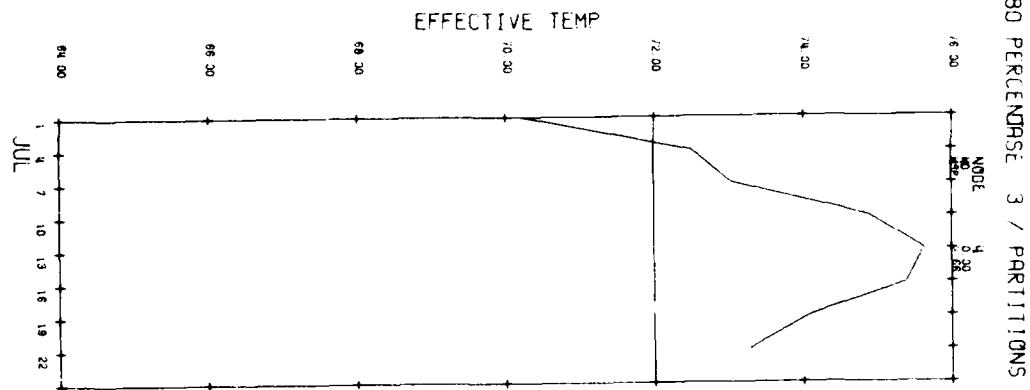
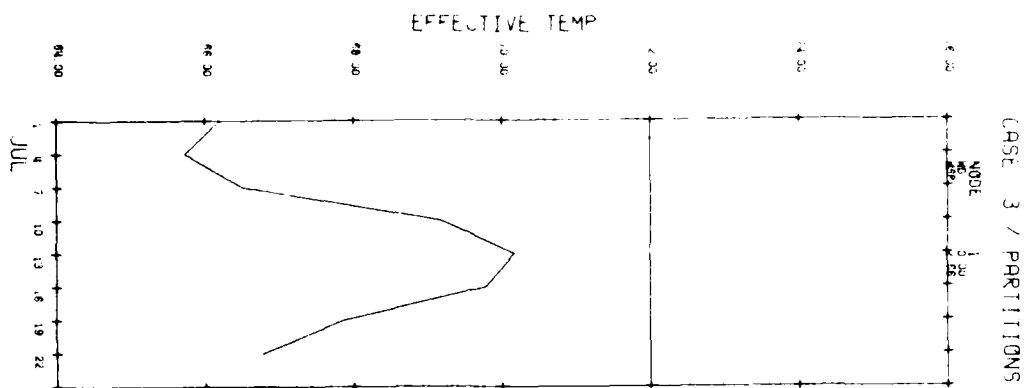
SUM OF FLOW ERROR= .00000

NO. OF CYCLES 1

NO. OF MATRIX INVERSIONS 0

NODE	PRESSURE	K	N	FLOW	MECH	AIR CHANGES	ROOM	PRESSURE	INTERIOR	MODE
FROM TO	DIFFERENCE			CMS	VENT CMS	RATE	VOLUME CM	PA	VEL FPM	
1 4	-.54571	33.7924000	.50	19.11057				2.118616		1
2 5	-.91441	33.7924000	.50	22.74133				2.542339		2
3 6	-.77424	47.5648000	.50	-41.85260				0.000000		3
4 1	-.54571	33.7924000	.50	-19.11057				1.472981		4
4 5	-.15502	1.9509000	.50	-.76813				1.472981		4
4 6	-.59866	33.7924000	.50	19.87880	.000	394.84	181.248	1.472901	131.61	4
5 2	-.91441	33.7924000	.50	-22.74133				1.627924		5
5 4	-.15502	1.9509000	.50	.76813				1.627924		5
5 6	-.45569	33.7924000	.50	21.97380	.000	451.71	191.248	1.627924	150.57	5
6 3	-.77424	47.5648000	.50	41.85260				.774236		6
6 4	-.59866	33.7924000	.50	-19.87890				.774236		6
6 5	-.85369	33.7924000	.50	-21.47380	.000	831.29	181.248	.774236	138.55	6

MONTH	HOUR	NODE	33F	dist	TEMP	PA	WD	WINDSP
JUL	13		72.20	72.30		23.720	0.00	2.66
		1	40.20	72.30	70.175			
		2	40.20	72.30	70.175			
		3	80.20	72.30	70.175			
		4	42.10	72.25	75.605			
		5	41.16	72.31	75.330			
		6	32.35	72.31	75.360			



In the computer program output the direction of flow is indicated by the sign. A negative sign in FLOW indicates that air flow INTO the room (or node). Dry-bulb, wet-bulb, and effective temperature for air LEAVING the room is also given.

#### 6.4 CONCLUSION

This computer simulation of natural ventilation cooling of buildings can be used as a tool for a preliminary study of a building design, to determine size of openings, required air flow, air changes, interior air velocity, and comfort ranges. In FY83 results of field testing and wind tunnel testing will be compared to results obtained from this computer program.

**Appendix A**

**WEATHER DATA EXAMPLES**

Table A-1. Means and Standard Deviations

Data Processing Division  
ETAC, USAF  
Asheville, N.C. 28801

22519 Station		Kaneohe Bay Oahu Hawaii MCAS Station Name												45-49, 52-65 Years											
Hours (LST)	Item	Dry-Bulb Temperatures (°F) From Hourly Observations																							
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual											
00-02	Mean	70.7	70.6	70.7	71.9	73.2	75.0	75.7	76.5	78.7	79.9	74.3	72.1	73.8											
	SD	2.574	2.441	2.134	1.866	1.540	1.240	1.217	1.214	1.243	1.568	1.861	2.344	2.891											
	Total Obs	1253	1109	1251	1311	1306	1305	1307	1302	1206	1243	1259	1306	15151											
03-05	Mean	70.2	70.2	70.2	71.4	72.7	74.5	75.2	76.0	76.1	75.3	73.8	71.6	73.1											
	SD	2.746	2.482	2.187	1.896	1.561	1.249	1.346	1.289	1.373	1.627	1.902	2.464	2.927											
	Total Obs	1252	1106	1246	1311	1305	1382	1319	1316	1231	1248	1262	1309	15207											
06-08	Mean	70.4	70.2	70.5	72.1	73.7	79.4	76.0	76.6	76.6	75.8	74.1	71.7	73.7											
	SD	2.808	2.575	2.416	2.172	2.050	1.799	1.751	1.621	1.800	1.916	2.140	2.544	3.224											
	Total Obs	1407	1266	1415	1455	1461	1398	1535	1556	1490	1504	1454	1476	17417											
09-11	Mean	73.8	73.7	74.0	75.4	76.9	78.5	79.0	79.7	80.1	79.4	77.6	74.8	77.0											
	SD	2.893	2.737	2.794	2.412	2.271	1.930	1.990	1.866	1.932	2.139	2.354	2.620	3.322											
	Total Obs	1509	1354	1497	1491	1481	1432	1575	1585	1534	1589	1530	1581	1											
12-14	Mean	75.8	75.5	75.6	76.6	78.0	79.7	80.2	81.0	81.2	80.6	78.0	76.4	78.3											
	SD	3.021	2.930	2.720	2.578	2.204	1.756	1.911	1.770	1.889	2.314	2.521	2.649	3.204											
	Total Obs	1502	1350	1495	1492	1481	1432	1574	1585	1535	1589	1526	1577	1513											
15-17	Mean	75.1	74.9	74.8	75.7	77.2	79.2	79.7	80.4	80.4	79.4	77.7	75.5	77.5											
	SD	2.940	2.854	2.727	2.397	2.181	1.711	1.802	1.658	1.719	2.135	2.375	2.470	3.131											
	Total Obs	1406	1319	1469	1478	1470	1414	1555	1560	1515	1569	1513	1549	17897											
18-20	Mean	70.7	72.4	72.6	73.4	74.8	76.7	77.5	78.1	78.0	77.8	75.6	73.4	75.2											
	SD	2.407	2.311	2.181	2.018	1.793	1.528	1.538	1.361	1.354	1.592	1.805	2.090	2.836											
	Total Obs	1462	1287	1446	1439	1427	1377	1503	1501	1445	1480	1459	1516	17341											
21-23	Mean	71.5	71.3	71.4	72.5	73.8	75.6	76.3	77.1	77.2	76.4	74.9	73.5	74.2											
	SD	2.368	2.268	2.050	1.814	1.577	1.195	1.231	1.181	1.173	1.453	1.795	2.189	2.799											
	Total Obs	1308	1141	1298	1346	1352	1342	1360	1336	1258	1288	1302	1342	15679											
All Hours	Mean	72.7	72.5	72.6	73.7	75.1	76.9	77.5	78.3	78.4	77.7	76.0	73.6	75.5											
	SD	3.419	3.271	3.140	2.872	2.710	2.471	2.456	2.381	2.467	2.670	2.799	2.995	3.591											
	Total Obs	11179	9932	11117	11323	11283	11002	11728	11741	11214	11510	11305	11836	134990											

Table A-2. Means and Standard Deviations

Data Processing Division  
ETAC, USAF  
Asheville, N.C. 28801

22519 Station		Kaneohe Bay Oahu Hawaii MCAS Station Name		45-49, 52-65 Years											
Hours (LST)	Item	Wet-Bulb Temperatures (°F) From Hourly Observations													
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual	
00-02	Mean	66.5	66.3	66.4	67.8	68.5	70.1	70.6	71.4	71.4	71.0	68.7	67.7	68.9	
	SD	2.540	2.733	2.504	2.153	1.709	1.247	1.451	1.474	1.482	1.660	1.992	2.474	2.779	
	Total Obs	1249	1107	1251	1309	1306	1304	1307	1302	1206	1237	1256	1306	16140	
03-05	Mean	66.1	66.0	66.0	67.1	68.2	69.8	70.4	71.2	71.1	76.6	69.4	67.4	68.6	
	SD	2.652	2.665	2.460	2.156	1.788	1.270	1.485	1.525	1.500	1.649	1.991	2.548	2.803	
	Total Obs	1251	1106	1246	1308	1305	1302	1319	1316	1231	1242	1259	1309	15194	
06-08	Mean	66.2	65.8	66.0	67.3	68.6	70.1	70.8	71.4	71.3	70.8	69.5	67.4	68.8	
	SD	2.694	2.700	2.489	2.258	1.868	1.440	1.568	1.519	1.517	1.671	2.104	2.596	2.916	
	Total Obs	1407	1266	1415	1453	1461	1398	1535	1556	1490	1499	1452	1476	17408	
09-11	Mean	67.7	67.1	67.4	68.5	69.9	71.3	71.9	72.5	72.5	72.1	70.8	68.7	70.1	
	SD	2.699	2.817	2.529	2.271	1.995	1.510	1.567	1.502	1.539	1.776	2.117	2.556	2.888	
	Total Obs	1509	1353	1497	1491	1480	1432	1574	1585	1534	1587	1530	1581	18	
12-14	Mean	68.3	67.8	68.0	68.9	70.3	71.7	72.3	72.9	72.9	72.5	71.2	69.2	70.5	
	SD	2.720	2.820	2.455	2.301	1.935	1.497	1.524	1.496	1.557	1.816	2.081	2.501	2.829	
	Total Obs	1502	1347	1495	1492	1481	1432	1575	1585	1535	1589	1526	1577	18136	
15-17	Mean	68.1	67.7	67.7	68.6	70.0	71.6	72.2	72.8	72.6	78.2	70.7	68.9	70.3	
	SD	2.632	2.744	2.497	2.219	1.903	1.453	1.462	1.413	1.519	1.778	1.961	2.496	2.794	
	Total Obs	1485	1318	1469	1478	1470	1414	1555	1661	1515	1569	1513	1549	17896	
18-20	Mean	67.3	66.8	66.9	67.8	69.2	70.7	71.4	71.9	71.8	71.4	70.1	68.2	69.5	
	SD	2.623	2.746	2.499	2.230	1.873	1.376	1.433	1.392	1.472	1.738	1.969	2.477	2.779	
	Total Obs	1459	1286	1446	1439	1427	1377	1503	1500	1445	1477	1459	1516	17334	
21-23	Mean	66.8	66.5	66.7	67.5	68.8	70.3	70.9	71.6	71.6	71.2	69.9	67.9	69.2	
	SD	2.537	2.725	2.533	2.196	1.809	1.269	1.453	1.406	1.444	1.766	1.936	2.488	2.761	
	Total Obs	1302	1138	1298	1346	1352	1342	1360	1336	1258	1282	1300	1342	15656	
All Hours	Mean	67.2	66.8	66.9	67.9	69.2	70.7	71.4	72.0	71.9	71.5	70.2	68.2	69.5	
	SD	2.760	2.834	2.597	2.324	2.008	1.554	1.646	1.602	1.634	1.855	2.177	2.600	2.903	
	Total Obs	11164	9821	11117	11116	11282	11001	11728	11741	11214	11482	11295	11656	134917	

Table A-3. Percentage Frequency of Wind Direction and Speed  
(From Hourly Observations)

Data Processing Division  
ETAC, USAF  
Asheville, N.C. 28801

Station: 22519		Station Name: Kaneohe Bay, Hawaii				Years: 73-77				Month: JUL			
Classification: All Weather													
Speed Dir. (knts)	1-3	4-6	7-10	11-16	17-21	22-27	28-33	24-40	41-47	48-55	>56	%	Mean Wind Speed
N		.1	.5									.6	8.1
NNE	.1	.6	1.3	.2								2.3	7.4
NE	.2	2.3	7.1	2.4								12.0	8.6
ENE	.9	5.2	23.5	21.7	.7							52.0	10.2
E	.2	3.6	11.5	14.0	.8	.1						30.2	10.5
ESE		.2	.3	.3								.8	10.3
SE		.1										.1	5.0
SSE	.1											.1	3.0
S	.2	.2	.2									.5	5.0
SSW		.2										.2	4.5
SW													
WSW													
W	.1											.1	3.0
WNW													
NW												.2	2.3
NNW	.2											1.0	
Varbl													
Calm	1.9	12.5	44.4	38.7	1.5	.1						100.0	9.9
Total Number of Observations: 1,240													

**Appendix B**

**PRESSURE COEFFICIENTS FOR RESIDENTIAL HOUSING  
AND COMMERCIAL BUILDINGS**

Table B-1. Wind at 45° Incidence to a Long Wall

(When data from Table B-1 and Table B-2 are used, set the pressure difference coefficient,  $\Delta C_p$ , equal to the windward pressure coefficient,  $C_{p_w}$ , and the leeward pressure coefficient,  $C_{p_L}$  equal to zero. So

$$\Delta C_p = C_{p_w}$$

and

$$C_{p_L} = 0)$$

Model Features	Average Pressure Differential Coefficient Between Mid-Height of Long Walls for Wind at 45 degrees Incidence to a Long Wall (Reference Pressure - Dynamic 10 Meters Above Ground in Wooded Suburban Terrain)
Single story elevated above ground with extended eaves and end walls (Type 4) <sup>a</sup>	0.75
Single story on-grade with extended eaves and end walls (Type 2) <sup>a</sup>	0.58
Single story elevated above ground (Type 3) <sup>a</sup>	0.43
Single story on-grade with flat roof (Type 6)	0.35
Single story on-grade with 10 degree pitch roof (Type 1)	0.34
Two story (Type 5)	0.31

<sup>a</sup>Note that the three highest ranking model types, 4, 2 and 3, at 45 degrees incidence were also highest ranking averaged over wind incidences of 0 degrees, 30 degrees and 45 degrees.

## 2.1 Pressure Coefficients for Buildings with Three Floors or Less.

Test data for side ratios of  $\gamma = 1.0, 0.5$  and  $0.25$  of model flat-roofed rectangular buildings have been accumulated and given in Graphs A, B, and C. When side ratio is close to one of these ratios, select the data for that ratio.

1. Wind direction, angle  $\alpha$ . Select wind incidence on long side, side 3, windward, and side 1 leeward from Figure B-2b.

2. The pressure coefficient,  $C_{p_3}$  windward ( $C_{p_w}$ ) is read from Graphs A, B, and C depending on the value of side ratio. The pressure coefficient  $C_{p_1}$  leeward ( $C_{p_2}$ ) is taken to be zero,  $C_{p_1} = 0$ .

3. Wind speed is calculated at roof height.

## 2.2 Pressure Coefficients for Tall Buildings.

Test data for side ratios of  $1.0, 0.5$  and  $0.25$  of model flat-roofed rectangular buildings have been accumulated and are given in Graphs D, E, and F. When side ratio is close to one of these ratios, select the data for that ratio.

1. Wind direction, angle  $\alpha$ . Select wind incidence on long side, side 3, windward, and side 1 leeward from Figure B-2b.

2. The pressure coefficient,  $C_{p_3}$  windward ( $C_{p_w}$ ) is read from Graphs D, E, and F depending on the value of side ratio. The pressure coefficient  $C_{p_1}$  leeward ( $C_{p_2}$ ) is taken to be zero,  $C_{p_1} = 0$ .

3. Calculate the local wind speed at mid-floor height.

Table B-2. Summary of Wind Pressure Difference Characteristics at Mid-Height of Walls on Six Types of Isolated Models at Wind Incidences, Normal, 30 Degrees and 45 Degrees to Long Walls

Model Features	Model Type	Overall Ranking Based on Average Pressure Diff. Coeff. Between Long Walls	Incidence to Long Wall (degrees)	Average Pressure Diff. Coeff. Between Long Walls	Maximum Pressure Diff. Coeff. Between Opposite Points on Long Walls	Minimum Pressure Diff. Coeff. Between Opposite Points on Long Walls
Single story on-grade	1	Worst	0 30 45	0.49 0.41 0.34	0.56 C 0.67 WE 0.71 WE	0.42 BE 0.10 LE -0.02 LE
Average				0.41		
Single story on-grade with extended eaves and end walls	2	2nd Best	0 30 45	0.51 0.66 0.58	0.56 C 0.71 WE 0.63 C	0.46 BE 0.58 LE 0.52 C
Average				0.58		
Single story elevated above ground	3	3rd Best	0 30 45	0.65 0.58 0.43	0.71 C 0.79 WE 0.81 WE	0.60 BE 0.33 LE 0.00 LE
Average				0.55		
Single story elevated above ground with extended verandas and end walls	4	Best	0 30 45	0.81 0.67 0.75	0.85 BE 0.75 LE 0.81 LE	0.77 C 0.50 WE 0.73 BE
Average				0.74		
Two story	5	5th Best	0 30 45	0.61 0.33 0.31	0.69 C 0.37 C 0.42 C	0.52 BE 0.24 WE 0.12 LE
Average				0.42		
Single story on-grade with flat roof	6	4th Best	0 30 45	0.51 0.42 0.35	0.58 C 0.69 WE 0.71 WE	0.44 BE 0.08 LE 0.00 LE
Average				0.43		

C = center one-third of long walls; BE = both ends of long walls; WE = windward ends of long walls; LE = leeward ends of long walls

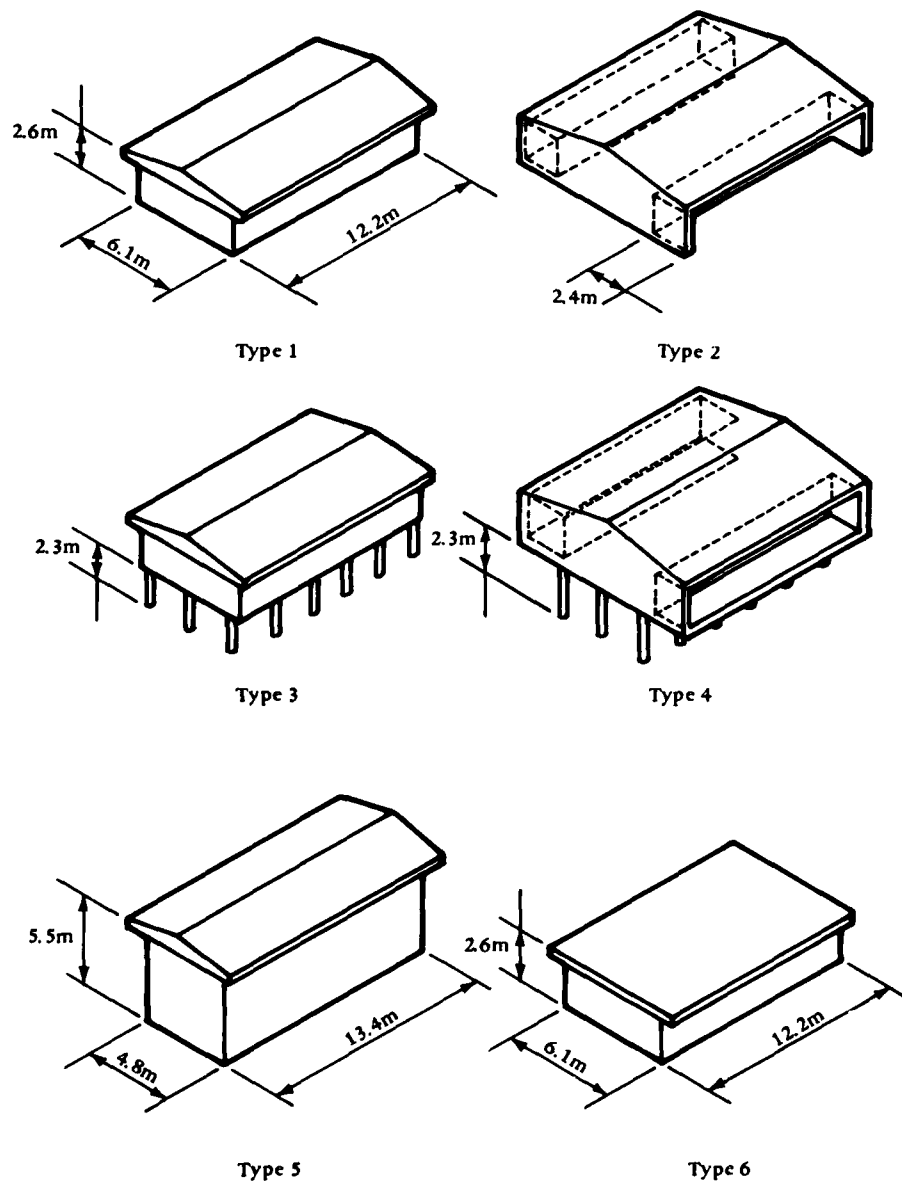
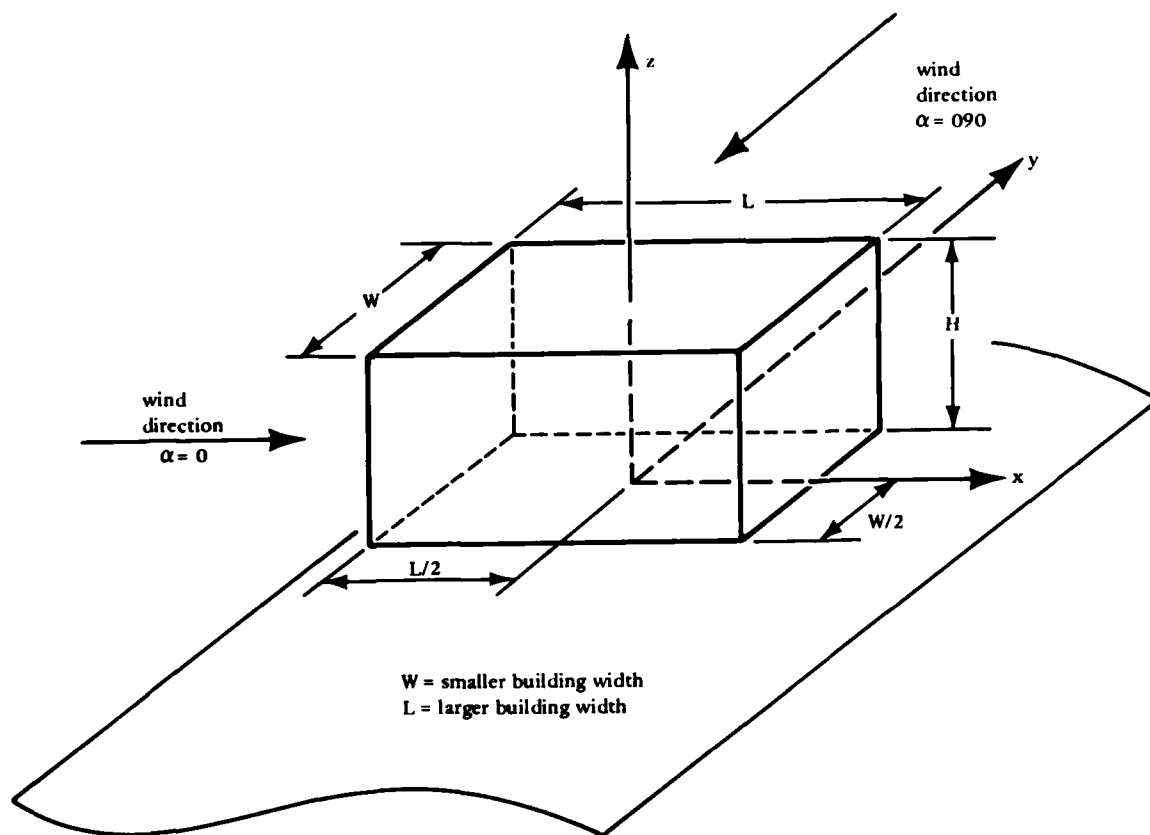


Figure B-1. Solid model types used in mid-wall height pressure distribution studies.



calculate side ratio:  $\gamma = \frac{\text{width of building}}{\text{length (larger side) of building}} = \frac{W}{L}$

Figure B-2a. Coordinate system of building.

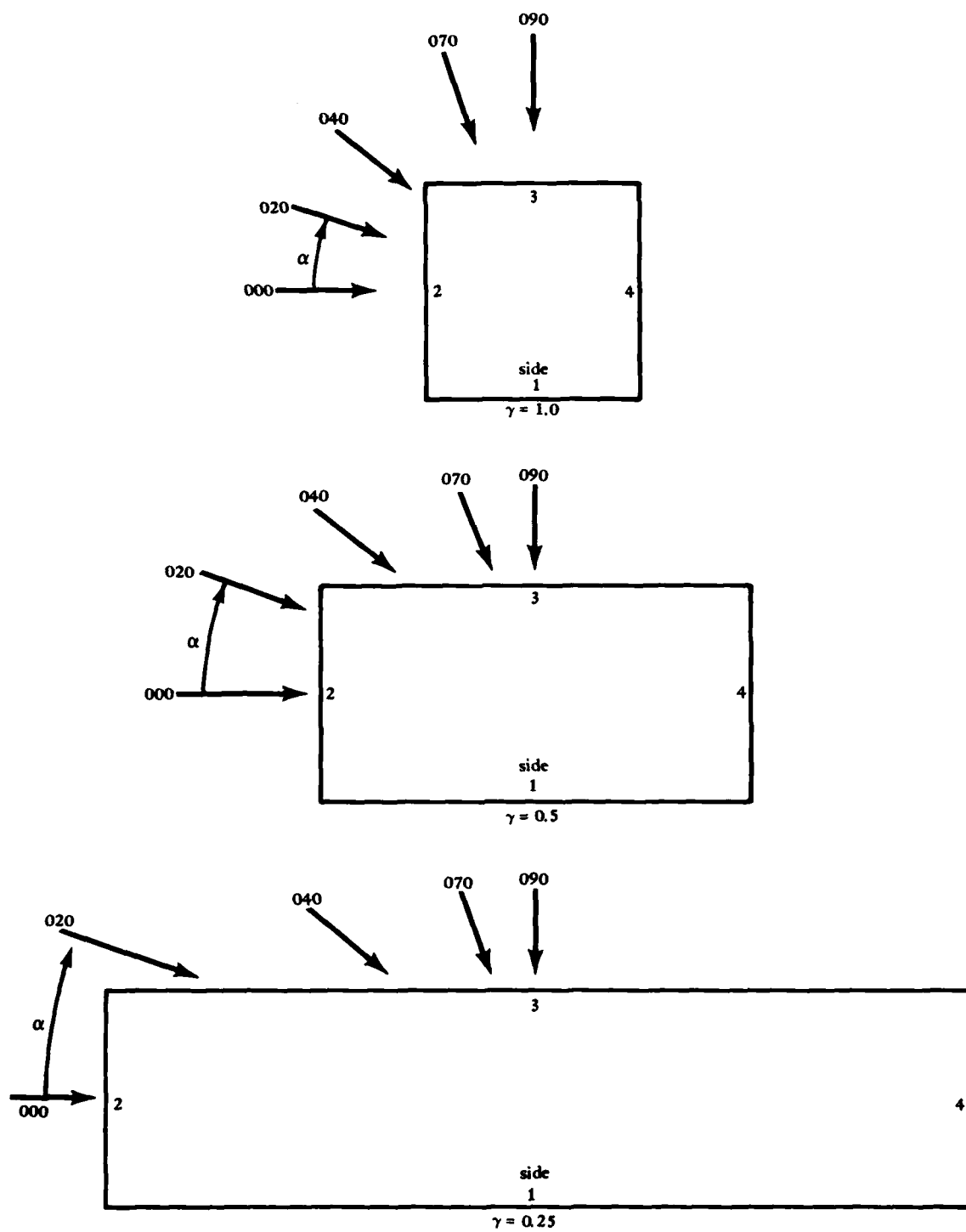
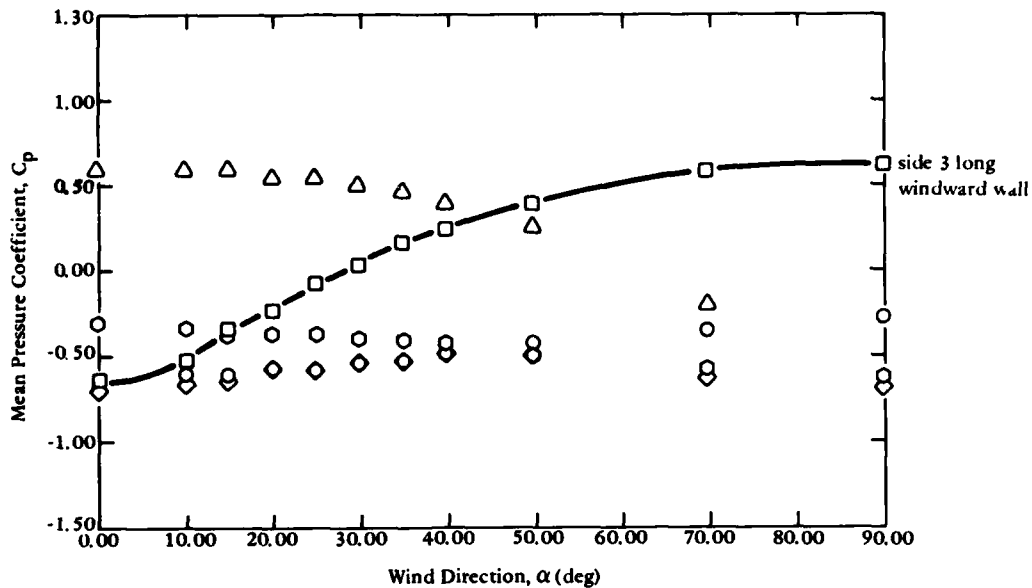
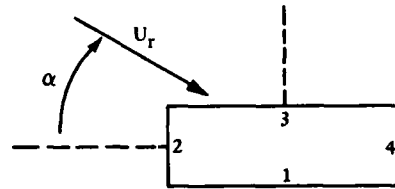


Figure B-2b. Wind directions on buildings.

Graphs: Pressure coefficients for buildings three stories height or less with a single value reference speed,  $U_r$ , at building roof height,  $\Delta C_p = C_{p3}$  ( $C_{p1} = 0$ ).

Gamma 1.00

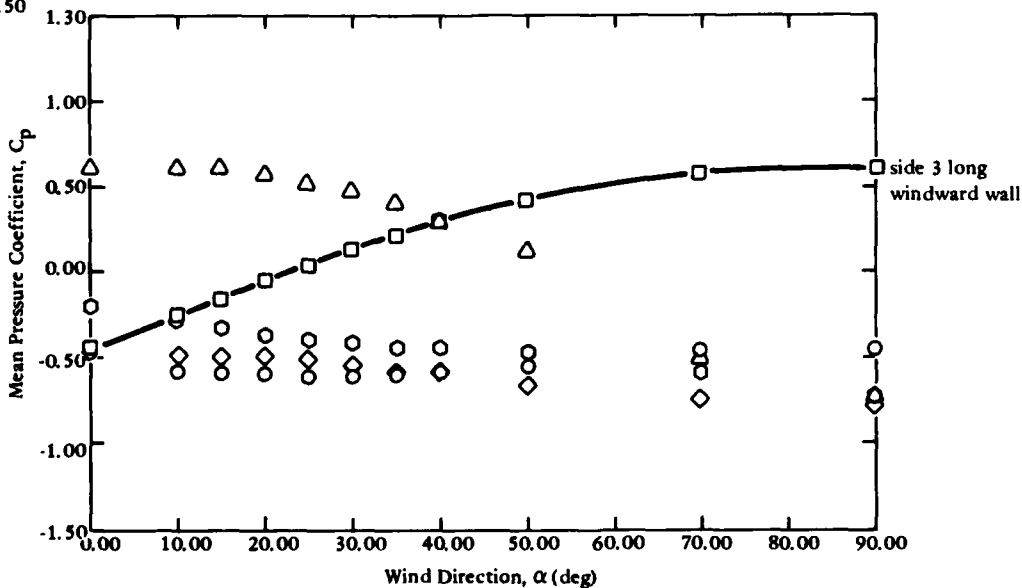
- Side 1
- △ Side 2
- Side 3
- Side 4
- ◇ Roof



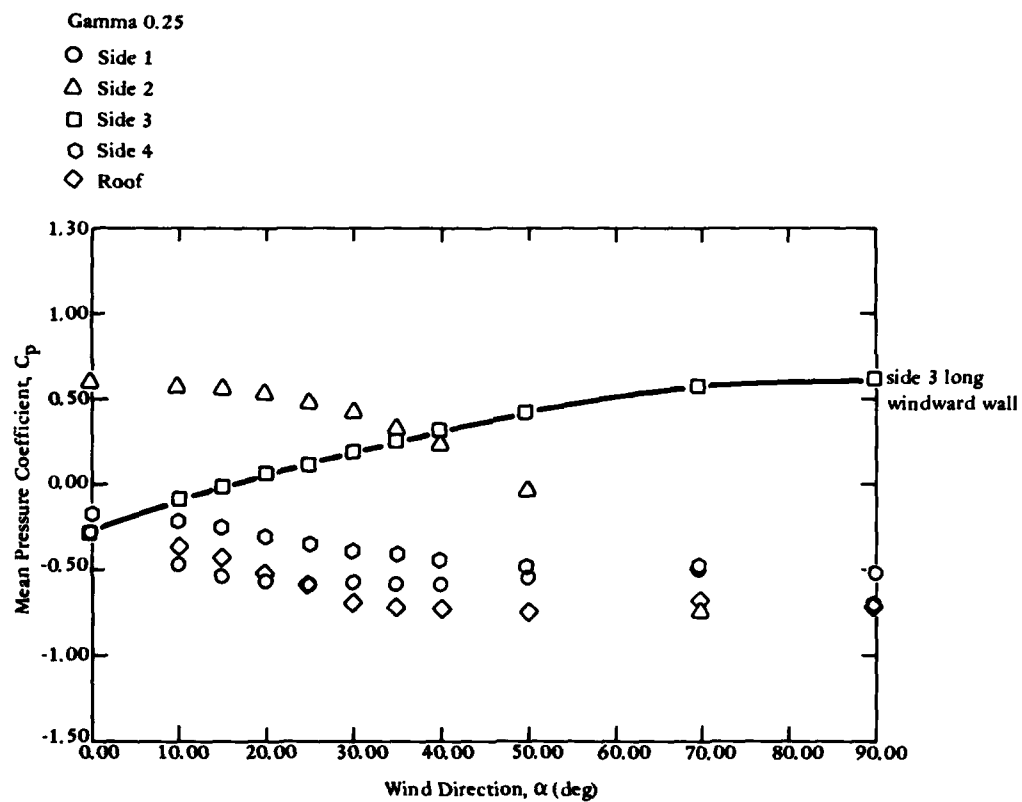
A. Averaged pressure coefficients based on a reference velocity measured at the roof,  $C_{pR}$ , for a side ratio of 1.0.

Gamma 0.50

- Side 1
- △ Side 2
- Side 3
- Side 4
- ◇ Roof



B. Averaged pressure coefficients based on a reference velocity measured at the roof,  $C_{pR}$ , for a side ratio of 0.5.

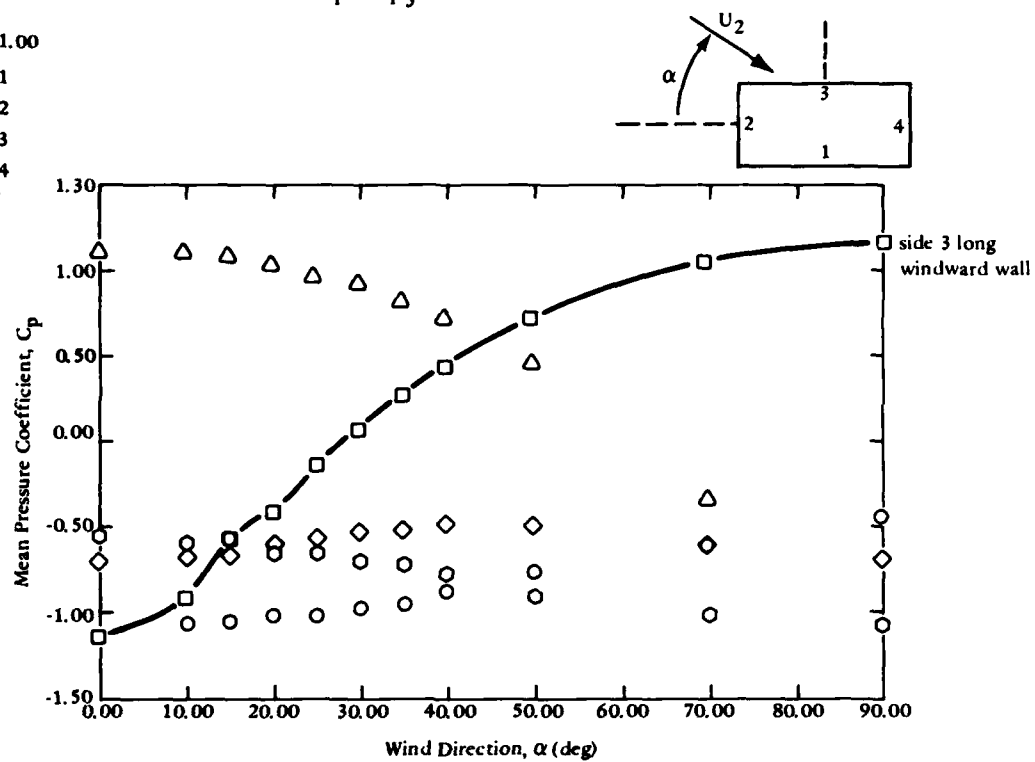


C. Averaged pressure coefficients based on a reference velocity measured at the roof,  $C_{PR}$ , for a side ratio of 0.25.

Graphs: Pressure coefficients for tall buildings for multiple values of reference velocity,  $U_2$ ,  $\Delta C_p = C_{p3}$ .

Gamma 1.00

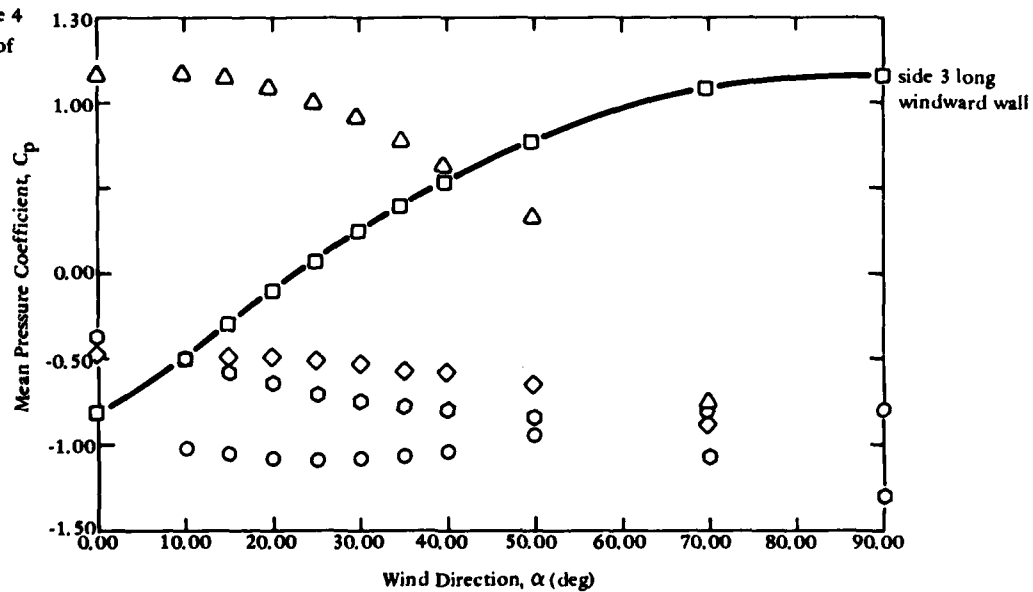
- Side 1
- △ Side 2
- Side 3
- Side 4
- ◇ Roof



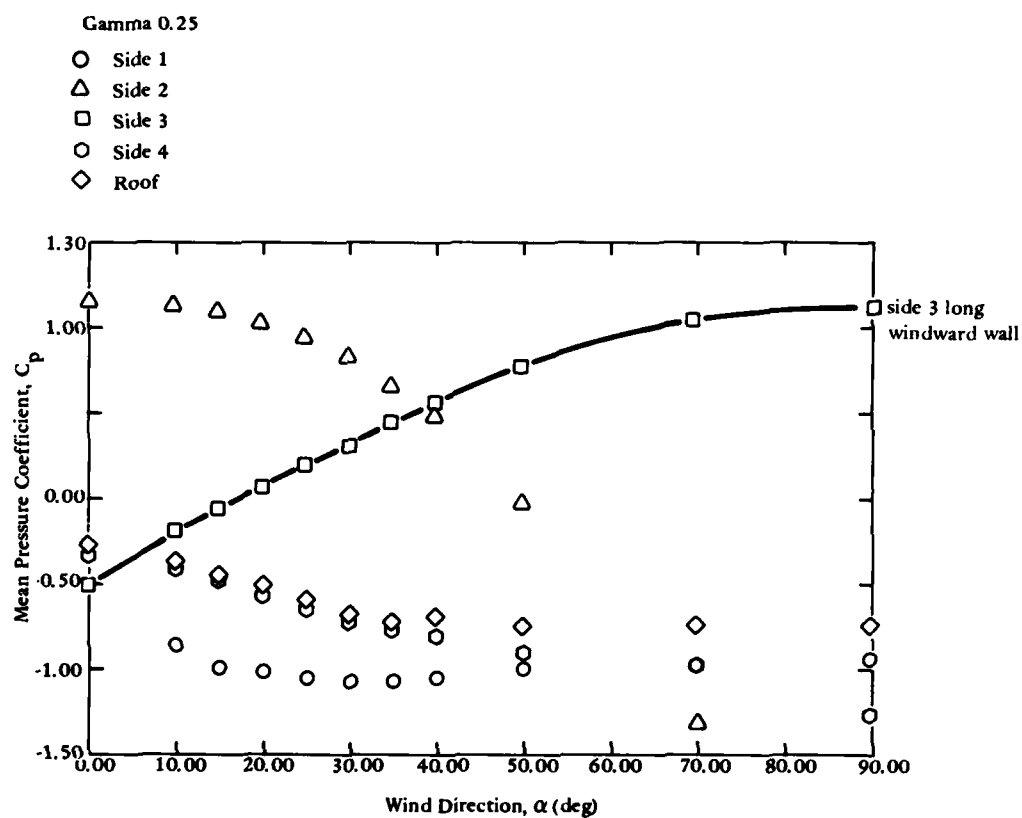
D. Averaged local pressure coefficients,  $C_{pL}$ , for a side ratio of 1.0.

Gamma 0.50

- Side 1
- △ Side 2
- Side 3
- Side 4
- ◇ Roof



E. Averaged local pressure coefficients,  $C_{pL}$ , for a side ratio of 0.5.



F. Averaged local pressure coefficients,  $C_{pL}$ , for a side ratio of 0.25.

**Appendix C**

**DISCHARGE COEFFICIENTS AND AIR LEAKAGE DATA  
FOR BUILDING COMPONENTS**

Table C-1. Typical Discharge Coefficients for Single Inlet or Intermediate Openings in Buildings

Description of Opening	Typical Range of Discharge Coefficients $C_d$ for Normal Incidence	Jet Characteristics
Small openings in thin walls less than 10% of wall area near the center of the wall	0.50 to 0.65	Small inertia due to small mass of air in jet
Openings 10 to 20% near the center of a wall with aspect ratio similar to the cross section of the downwind space	0.65 to 0.70	Significant inertia due to increased mass of air in jet
Openings 10 to 20% of a wall with one edge common with the downwind space such as a doorway	0.70 to 0.80	Wall effect reduces energy losses on one side of jet
Openings similar in size to the cross section of the downstream space	0.80 to 0.90	Wall effect around the perimeter of the jet significantly reduces turbulent energy losses

# Typical Discharge Coefficients for Leeward Outlet Openings

$A_D/A_1$	$C_D$
Approaching	
0.0	0.63
0.2	0.64
0.4	0.67
0.6	0.71
0.8	0.81
1.0	1.00

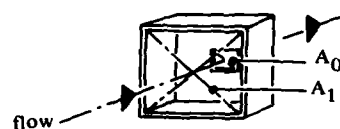


Table C-2. Summary of Air Leakage Data for Building Components Taken From Various Sources

Component	Description	Average Leakage in 1/s for $\Delta p = 25 \text{ Pa}$	Value of Index N	Remarks
Windows	Pivoted	1.60 per meter crack	1.6	Leakage range 0.42 to 5.7
	Pivoted and weatherstripped	0.22 per meter crack	1.6	Leakage range 0.035 to 1.5
	Sliding	0.61 per meter crack	1.6	Leakage range 0.15 to 2.3
Doors	Proposed Grading:			
	Sheltered exposure	1.40 per meter crack	1.6	
	Moderate exposure	1.08 per meter crack	1.6	
	Severe exposure	0.91 per meter crack	2.0	
	Single stairwell	75 per meter crack	2.0	
	Lift door	200 per meter crack	2.0	
	External door with sill	8 per meter crack	2.0	
Brick and Masonry	Standard fire stop door with 1/8 in. (3 mm) gap	13 per meter crack	2.0	Computed value
	Lift door with 3/16 in. (5 mm) gap	21 per meter crack	2.0	Computed value
	8-1/2 in. (216 mm) plain brick	0.76 per $\text{m}^2$	1.15	
	8-1/2 in. (216 mm) plain with plaster	0.0068 per $\text{m}^2$	1.15	
	13 in. (330 mm) plain brick	0.68 per $\text{m}^2$	1.15	
	13 in. (330 mm) plain brick with plaster	0.0034 per $\text{m}^2$	1.15	
	External walls	1 to 2 per $\text{m}^2$ for curtain wall	2.0	The leakage through completed structures is assumed to be through cracks, hence value of $N = 2$
	Internal walls	200 per floor unplastered 400 per floor unplastered	2.0 2.0	
	Floors	1 per $\text{m}^2$	2.0	

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MCAS Facil. Engr. Div. Cherry Point NC; CO, Kaneohe Bay HI; Code S4, Quantico VA; Facs Maint Dept - Operations Div. Cherry Point; PWD - Utilities Div. Iwakuni, Japan; PWO, Iwakuni, Japan; PWO, Yuma AZ

MCDEC M&L Div (LTC R. Keff) Quantico, VA; M&L Div Quantico VA; NSAP REP. Quantico VA

MCLB B520, Barstow CA; Maintenance Officer, Barstow, CA; PWO, Barstow CA

MCRD SCE, San Diego CA

NAF PWD - Engr Div. Atsugi, Japan; PWO, Atsugi Japan

NALF OINC, San Diego, CA

NARF Code 100, Cherry Point, NC; Code 612, Jax, FL; Code 640, Pensacola FL; SCE Norfolk, VA

NAS CO, Guantanamo Bay Cuba; Code 114, Alameda CA; Code 183 (Fac. Plan BR MGR); Code 187, Jacksonville FL; Code 18700, Brunswick ME; Code 18U (ENS P.J. Hickey), Corpus Christi TX; Code 8E, Patuxent Riv., MD; Dir of Engrng. PWD, Corpus Christi, TX; Dir. Util. Div., Bermuda; Grover, PWD, Patuxent River, MD; Lakehurst, NJ; Lead. Chief. Petty Offr. PW/Self Help Div. Beeville TX; PW (J. Maguire), Corpus Christi TX; PWD - Engr Div Dir. Millington, TN; PWD - Engr Div. Gtmo, Cuba; PWD - Engr Div. Oak Harbor, WA; PWD Maint. Cont. Dir., Fallon NV; PWD Maint. Div., New Orleans, Belle Chasse LA; PWD, Code 1821H (Pfankuch) Miramar, SD CA; PWD, Maintenance Control Dir., Bermuda; PWD, Willow Grove PA; PWO Belle Chasse, LA; PWO Chase Field Beeville, TX; PWO Key West FL; PWO Lakehurst, NJ; PWO Sigonella Sicily; PWO Whiting Fld, Milton FL; PWO, Dallas TX; PWO, Glenview IL; PWO, Millington TN; PWO, Miramar, San Diego CA; SCE Norfolk, VA; SCE, Barbers Point HI; SCE, Cubi Point, R.P

NASDC-WDC T. Fry, Manassas VA

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NAVAIRDEVCCEN Chmielewski, Warminster, PA; PWD, Engr Div Mgr. Warminster, PA

NAVAIRPROTESTCEN CO, Trenton, NJ

NAVAIRSYSCOM Code 41712A (Michols) Washington, DC

NAVAIRTESTCEN PATUXENT RIVER PWD (F. McGrath), Patuxent Riv., MD

NAVCHAPGRU Operations Officer, Code 30 Williamsburg, VA

NAVCOASTSYSCEN CO, Panama City FL; Code 715 (J Quirk) Panama City, FL; Code 772 (C B Koesy) Panama City FL; Library Panama City, FL; PWO Panama City, FL

NAVCOMMAREAMSTRSTA PWO, Norfolk VA; SCE Unit 1 Naples Italy; SCE, Wahiawa HI

NAVCOMMSTA Code 401 Nea Makri, Greece; PWD - Maint Control Div. Diego Garcia Is.; PWO, Exmouth, Australia; SCE, Balboa, CZ

NAVCONSTRACEN Code 00U15, Port Hueneme CA; Curriculum/Instr. Stds Offr. Gulfport MS

NAVEDTRAPRODEVCCEN Technical Library, Pensacola, FL

NAVEDUTRACEN Engr Dept (Code 42) Newport, RI

NAVEODTECHCEN Code 605, Indian Head MD

NAVFAC PWO, Brawdy Wales UK; PWO, Centerville Bch, Ferndale CA; PWO, Point Sur, Big Sur CA

NAVFACENGCOM Alexandria, VA; Code 03 Alexandria, VA; Code 03T (Essoglou) Alexandria, VA; Code 043 Alexandria, VA; Code 044 Alexandria, VA; Code 044B Alexandria, VA; Code 0451 (P W Brewer) Alexandria, VA; Code 0451, Alexandria, VA; Code 04A1 Alexandria, VA; Code 04B3 Alexandria, VA; Code 051A Alexandria, VA; Code 06, Alexandria VA; Code 09M54, Tech Lib, Alexandria, VA; Code 100 Alexandria, VA; Code 1113, Alexandria, VA; Code 111B Alexandria, VA; code 08T Alexandria, VA

NAVFACENGCOM - CHES DIV. Code 403 Washington DC; Code 405 Wash, DC; FPO-1 Washington, DC; Library, Washington, D.C.

NAVFACENGCOM - LANT DIV. Code 111, Norfolk, VA; Code 403, Norfolk, VA; Code 405 Civil Engr BR Norfolk VA; Eur. BR Deputy Dir, Naples Italy; Library, Norfolk, VA; RDT&ELO 102A, Norfolk, VA

NAVFACENGCOM - NORTH DIV. Code 04 Philadelphia, PA; Code 09P Philadelphia PA; Code 1028, RDT&ELO, Philadelphia PA; Code 111 Philadelphia, PA; Library, Philadelphia, PA; ROICC, Contracts, Crane IN

NAVFACENGCOM - PAC DIV. (Kyi) Code 101, Pearl Harbor, HI; CODE 09P PEARL HARBOR HI; Code 2011 Pearl Harbor, HI; Code 402, RDT&E, Pearl Harbor HI; Commander, Pearl Harbor, HI; Library, Pearl Harbor, HI

NAVFACENGCOM - SOUTH DIV. Code 403, Gaddy, Charleston, SC; Code 90, RDT&ELO, Charleston SC; Library, Charleston, SC

NAVFACENGCOM - WEST DIV. AROICC, Contracts, Twentynine Palms CA; Code 04B San Bruno, CA; Library, San Bruno, CA; 09P/20 San Bruno, CA; RDT&ELO Code 2011 San Bruno, CA

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Balboa Panama Canal; ROICC AF Guam; ROICC Code 495 Portsmouth VA; ROICC Key West FL;  
 ROICC MCAS El Toro; ROICC, Keflavik, Iceland; ROICC, NAS, Corpus Christi, TX; ROICC, Pacific, San  
 Bruno CA; ROICC, Yap; ROICC-OICC-SPA, Norfolk, VA  
 NAVHOSP PWD - Engr Div, Beaufort, SC  
 NAVMAG PWD - Engr Div, Guam; SCE, Subic Bay, R.P.  
 NAVOCEANSYSCEN Code 4473B (Tech Lib) San Diego, CA; Code 523 (Hurley), San Diego, CA; Code 6700,  
 San Diego, CA; Code 811 San Diego, CA  
 NAVORDMISTESTFAC PWD - Engr Dir, White Sands, NM  
 NAVORDSTA PWD - Dir, Engr Div, Indian Head, MD; PWO, Louisville KY  
 NAVPETOFF Code 30, Alexandria VA  
 NAVPETRES Director, Washington DC  
 NAVPHIBASE CO, ACB 2 Norfolk, VA; Code S3T, Norfolk VA; SCE Coronado, SD, CA  
 NAVREGMEDCEN PWD - Engr Div, Camp Lejeune, NC; PWO, Camp Lejeune, NC  
 NAVREGMEDCEN PWO, Okinawa, Japan  
 NAVREGMEDCEN SCE; SCE San Diego, CA; SCE, Camp Pendleton CA; SCE, Guam; SCE, Newport, RI;  
 SCE, Oakland CA  
 NAVREGMEDCEN SCE, Yokosuka, Japan  
 NAVSCOLCECOFF C35 Port Hueneme, CA  
 NAVSCSOL PWO, Athens GA  
 NAVSEASYSOM Code 0325, Program Mgr, Washington, DC; Code PMS 395 A 3, Washington, DC; SEA  
 (HE (L Kess) Washington, DC  
 NAVSECGRUACT PWO, Adak AK; PWO, Edzell Scotland; PWO, Puerto Rico; PWO, Torri Sta, Okinawa  
 NAVSECSTA PWD - Engr Div, Wash., DC  
 NAVSHIPYD Code 202.4, Long Beach CA; Code 202.5 (Library) Puget Sound, Bremerton WA; Code 380,  
 Portsmouth, VA; Code 382.3, Pearl Harbor, HI; Code 400, Puget Sound; Code 410, Mare Is., Vallejo CA;  
 Code 440 Portsmouth NH; Code 440, Norfolk; Code 440, Puget Sound, Bremerton WA; Code 453 (Util,  
 Supr), Vallejo CA; Library, Portsmouth NH; PW Dept, Long Beach, CA; PWD (Code 420) Dir Portsmouth,  
 VA; PWD (Code 450-HD) Portsmouth, VA; PWD (Code 453-HD) SHPO 03, Portsmouth, VA; PWO,  
 Bremerton, WA; PWO, Mare Is.; PWO, Puget Sound; SCE, Pearl Harbor HI; Tech Library, Vallejo, CA  
 NAVSTA Adak, AK; CO, Brooklyn NY; Code 4, 12 Marine Corps Dist, Treasure Is., San Francisco CA; Dir  
 Engr Div, PWD, Mayport FL; Dir Mech Engr 37WC93 Norfolk, VA; Engr, Dir., Rota Spain; Long Beach,  
 CA; Maint. Cont. Div., Guantanamo Bay Cuba; Maint. Div. Dir/Code 531, Rodman Panama Canal; PWD -  
 Engr Dept, Adak, AK; PWD - Engr Div, Midway Is.; PWO, Keflavik Iceland; PWO, Mayport FL; SCE,  
 Guam; SCE, Pearl Harbor HI; SCE, San Diego CA; SCE, Subic Bay, R.P.; Utilities Engr Off, Rota Spain  
 NAVSUPPACT CO, Naples, Italy; PWO Naples Italy  
 NAVSUPPFAC PWD - Maint. Control Div, Thurmont, MD  
 NAVSURFWPCEN PWO, White Oak, Silver Spring, MD  
 NAVTECHTRACEN SCE, Pensacola FL  
 NAVTELCOMMCOM Code 53, Washington, DC  
 NAVWPN/CEN Code 2636 China Lake; Code 3803 China Lake, CA; PWO (Code 266) China Lake, CA; ROICC  
 (Code 702), China Lake CA  
 NAVWPNSTA (Clebak) Colts Neck, NJ; Code 092, Concord CA; Code 092A, Seal Beach, CA  
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 Charleston, SC; PWO, Seal Beach CA  
 NAVWPNSUPPCEN Code 09 Crane IN  
 NCTC Const. Elec. School, Port Hueneme, CA  
 NCBC Code 10 Davisville, RI; Code 15, Port Hueneme CA; Code 155, Port Hueneme CA; Code 1552 (Brazele)  
 Port Hueneme, CA; Code 155B (Nishimura) Port Hueneme, CA; Code 156, Port Hueneme, CA; Code 156F  
 (Volpe) Port Hueneme, CA; Code 25111 Port Hueneme, CA; Code 430 (PW Engrng) Gulfport, MS; Code  
 470.2, Gulfport, MS; NEESA Code 252 (P Winters) Port Hueneme, CA; PWO (Code 80) Port Hueneme,  
 CA; PWO, Davisville RI; PWO, Gulfport, MS  
 NCR 20, Code R70; 20, Commander  
 NMCB 3, SWC D, Wellington; 74, CO; FIVE, Operations Dept; Forty, CO; THREE, Operations Off.  
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 NRL Code 5800 Washington, DC  
 NROTC J.W. Stephenson, UC, Berkeley, CA  
 NSC Code 54.1 Norfolk, VA  
 NSD SCE, Subic Bay, R.P.  
 NSWSES Code 0150 Port Hueneme, CA  
 NTC OICC, CBU-401, Great Lakes IL  
 NUSC Code 131 New London, CT; Code 5202 (S. Schady) New London, CT; Code EA123 (R.S. Munn), New  
 London CT; Code SB 331 (Brown), Newport RI  
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 PACMISRAFAC HI Area Bkg Sands, PWO Kekaha, Kauai, HI

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 Pearl Harbor HI: Code 10, Great Lakes, IL: Code 105 Oakland, CA: Code 110, Great Lakes, IL: Code 110,  
 Oakland, CA: Code 120, Oakland CA: Code 128, Guam: Code 154 (Library), Great Lakes, IL: Code 200,  
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 700, Great Lakes, IL: Library, Code 120C, San Diego, CA: Library, Guam: Library, Norfolk, VA: Library,  
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